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Experimental Measurement Method and Evaluation of an Analytical Approach for Sound Conduction through Multiple Clinched Sheets †

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Abstract: The conduction of structure-borne sound through joints causes energy dissipation. The sound reduction index describes this energy loss as a level decrease in the particle velocity across series-connected damping elements for which the superposition principle applies. This simple model can help to develop a testing method for joints based on this characteristic energy loss. In this paper, this model is experimentally evaluated for multiple in-series clinched aluminium sheets. Samples connected by several clinch points arranged in parallel are investigated experimentally, and the results are discussed.

Keywords: clinching; mechanical joining; damping; model; evaluation; dynamics

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1. Introduction

Clinching is a cost-efficient [1] mechanical joining process that creates a force and form closure [2] between two or more flat partners by forming. The window technique is often used for process monitoring during the clinching process. The force and displacement curves are observed over time and compared with set tolerances [3]. This method allows a rough process control, but not a detailed analysis of property-determining geo- metric values. Particularly important property-determining geometrical parameters are the interlock f and the neck thickness t_n [4]. These dimensions can only be measured destructively by preparing a microsection or non-destructively by means of radiographic testing [5]. Both methods are relatively time-consuming, cost-intensive and require expert knowledge and handling of samples. Currently, only visual inspection is available as a cost-effective inspection method for clinched joints. However, certain defects cannot be detected by visual inspection. For example, the formation of cracks in the clinch connection is not always visible from the outside [6]. In terms of sustainability and safety, it is necessary to develop suitable testing procedures in order to non-destructively check clinched structures for damage during their lifetime. This is the precondition for a specific repair or service life extension of the structure.

A promising approach to address these issues is the transient dynamic analysis (TDA), which combines acoustic analysis with fast signal evaluation and offers the potential to detect quickly and non-destructively irregularities in a clinch joint [7]. The process involves the targeted introduction of sound waves into a joining partner. The characteristic damping of the sound waves in the joint changes their characteristics. These changed, structure-borne sound waves arriving on the other joining partner are detected by means of piezoelectric sensors and then evaluated. Köhler et al. have shown in a numerical study that clinch points with varying bottom thicknesses are different in their dynamic behaviour [8]. This technique has already been practised successfully with regard to bolted joints. Wolf et al.

observe a reduced energy loss of the sound waves when passing through the joint with an increasing tightening torque [9].

Wang et al. determine the residual preload force via the dissipation of energy in a bolted joint [10]. These studies all investigate damping across a single joint. However, in real structures, connections with only one joint are rare. In most cases, there are multiple clinch points or bolted joints connecting two parts of a structure. In order to apply findings from investigations on individual joining points to complex multi-joint structures using TDA as a testing method, it is necessary to evaluate how the damping of structure-borne sound waves changes when several clinch points connect two components in parallel. Real structures often consist of more than two components, so damping through multiple joints and components in series is also a relevant scenario.

One approach is to directly use the empirical data of a specific multi-clinched structure. By comparing the experimentally determined data for a specific defect-free structure with multiple clinch joints, deviations within a series or across the time of use on a single structure can be detected.

A more elegant approach is to use an analytical model to calculate the damping for a complex defect-free clinched structure from the measurement of the damping of a single clinch point.

One aim of this paper is to test an experimental measurement method to determine the sound damping across multiple clinched structures. The second aim of this paper is to evaluate a simple semi-analytical model that could help to apply TDA as a testing method for more complex structures. Schmidt explains the mathematical relationship between the sound reduction index (Figure 1A) with masses m_i and velocities v_i and the insertion sound reduction index (Figure 1B) wit masses m_i and velocities v_{i*}.

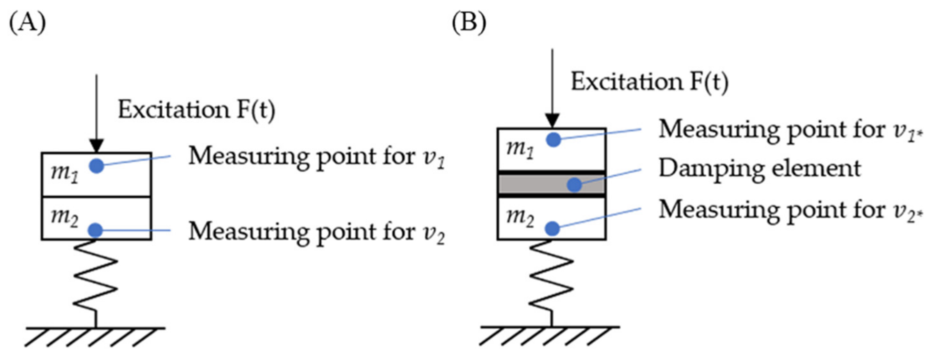

Figure 1. Schematic representation of (**A**) sound reduction index and (**B**) insertion sound reduction index [11].

The sound reduction index ΔL_{Dv*} is the level difference of the structure-borne particle velocity v between two masses which are separated by a sound-damping element (Figure 1b).

$$\Delta L_{Dv*} = 20 \times \log_{10}\left|\frac{v_1}{v_2}\right| \tag{1}$$

This level difference is proportional to the level difference of the sound power and is used for the evaluation of sound damping methods. The insertion sound reduction index

ΔL_{DE} describes the damping effect of a damping element as a comparison of the levels that are achieved at a defined point with (quantities with *) and without (quantities without *) the damping element [11].

$$\Delta L_{DE} = \Delta L_{Dv*} - \Delta L_{Dv} \tag{2}$$

Or rather

$$\Delta L_{DE} = 20 \times \log_{10}\left|\frac{v_{1*} \cdot v_2}{v_{2*} \cdot v_1}\right| \tag{3}$$

When calculating the insertion sound reduction index according to Equation (2), levels of different systems are simply subtracted from each other as if the superposition principle would apply to this structure-borne sound problem. This paper investigates whether this simplification can be applied to the problem of sound damping in clinch joints. The sound-damping element is therefore a clinch point here. If the superposition principle is valid for this problem or represents a good approximation, then it should be possible to calculate the sound reduction index for further clinching points on a structure that are in series with each other from the determination of an insertion sound reduction index for one clinching point (see Figure 2).

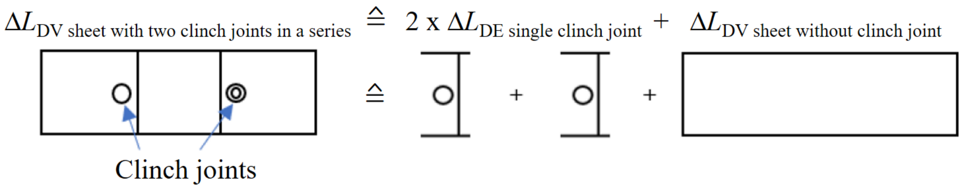

Figure 2. Visualization of the superposition principle to two clinching points in series.

2. Materials and Methods

2.1. Samples

Seven different sample series of three specimens per series are used for the tests. The specimens consist of sheets of the aluminium material EN AW 6014 with a thickness of 2.0 mm. They all have the same external dimensions of 60 mm × 200 mm but different numbers of clinch points or different arrangements of clinch points (see Figure 3). The used die (type BE8012) and the punch (type A50100) are made by TOX Pressotechnik GmbH & Co.KG, Weingarten, Germany. The bottom thickness of the clinch joints is 0.68 mm for all samples. The overlap is 20 mm for all clinch joints.

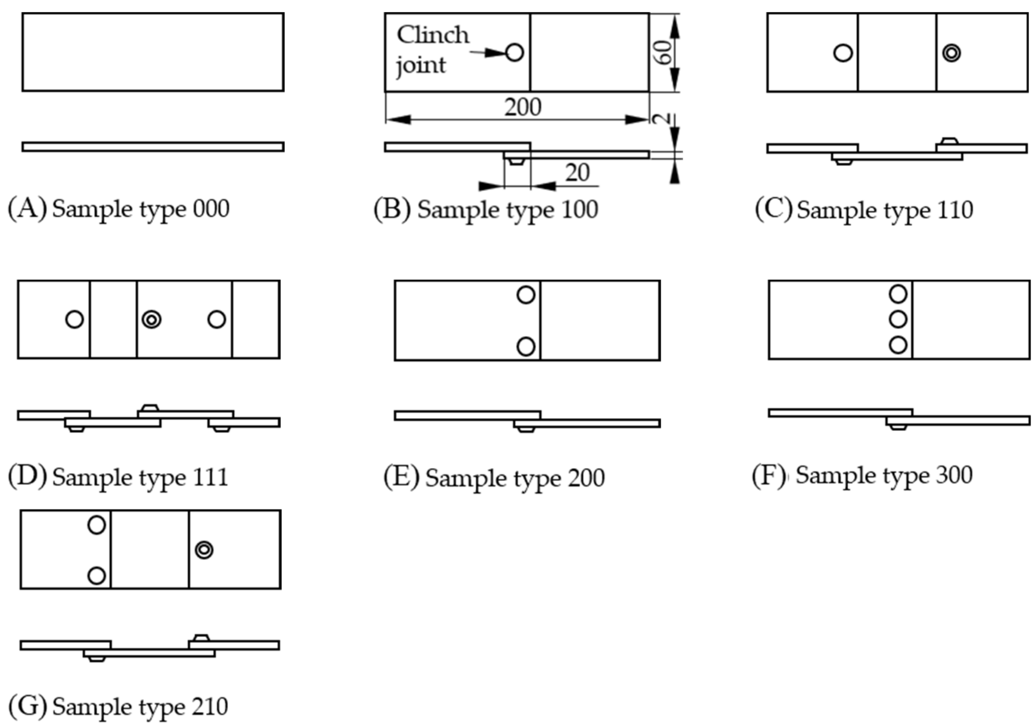

Figure 3. Clinched samples of aluminium sheet EN AW 6014.

2.2. Test Rig and Measurement Method

The clinched samples are clamped in the sample holder in a defined way at both ends. The four bolts are tightened to 10 Nm with a torque key, see Figure 4a. The piezoelectric stack actuator (type P-016.00H, PI Ceramic GmbH, Lederhose, Germany), which introduces the sound into the experimental setup, is located on the left side of the frame. The excitation signal for the stack actuator is generated by the signal generator of the scanning laser-Doppler-vibrometer (SLDV) for short and amplified by a piezo amplifier (type HV-LE150-100-EBW, piezosystem jena GmbH, Jena, Germany) by a factor of 30. The SLDV (manufactured by Optomet GmbHm, Darmstadt, Germany) allows non-contact, two-dimensional measurement of the particle velocity on the surface of the specimen. In contrast to single-point LDVs, the SLDV measures all points on a freely definable point grid on the surface of a body one after the other. The two areas with 40 individual measuring points each, which are analysed for all samples, are shown in Figure 4b.

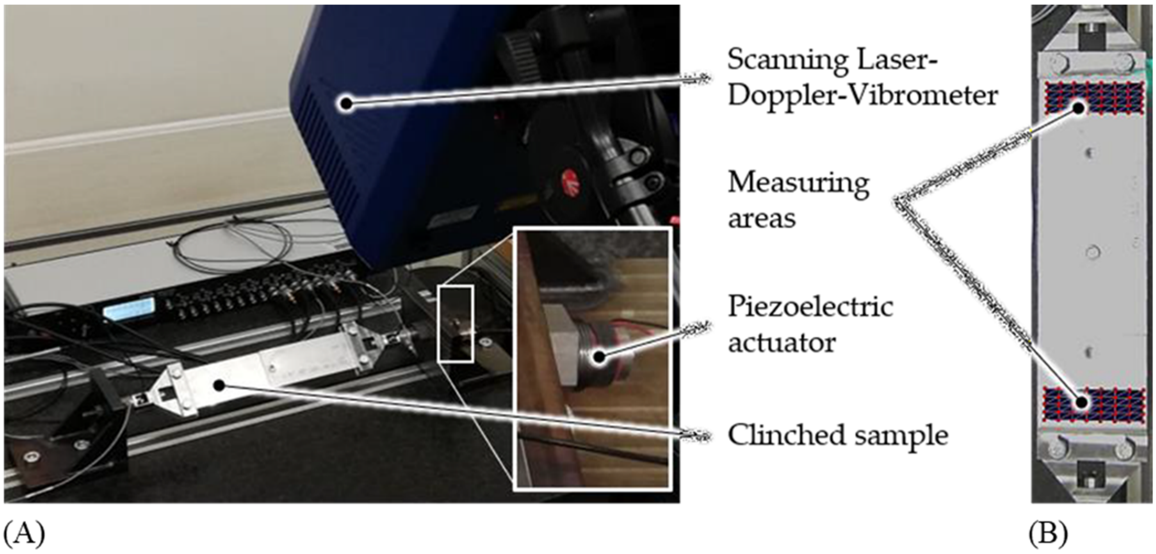

Figure 4. (**A**) Photo of test rig with clamped sample; (**B**) measuring areas.

A prerequisite for successful phase alignment between the measurements of the individual points is a periodic process that triggers the measurement of the SLDV. In the present case, this periodic process is the excitation of the piezoelectric actuator by the signal generator of the SLDV. The selected excitation is a chirp signal which passes through a harmonic excitation of 80 Hz up to 64 kHz at 3 V peak voltage. The stack actuator is excited with a peak voltage of 90 V by the signal amplification. Measurement data are recorded in the time domain for each individual point. A high-pass filter of 80 Hz cut-off frequency and a low-pass of 100 kHz are set. With the help of the Fast Fourier transform FFT, a frequency spectrum (spectral resolution 10 Hz) is created for each point. The resulting amplitudes at a certain frequency are averaged for each of the two surfaces, i.e., from 40 individual points. This averaging reduces the strong local dependence of the resonance behaviour. Then, the amplitudes are averaged over the frequency band of the ex- citation, so that for each sample only two values for the particle velocity remain at the end. One describes the particle velocity on the actuator side of the sample and the other the particle velocity on the non-actuator side of the sample. These values are then used to calculate the sound reduction index ΔL_{Dv} or the insertion sound reduction index ΔL_{DE}.

3. Results and Discussion

The measurement area and frequency band averaged values for the particle velocity on the actuator side and the non-actuator side were measured for each sample. From these values for the particle velocity, the sound reduction index was calculated for each sample according to Equation (1). The values for sound reduction index ΔL_{Dv} averaged over the same sample type are given in the following Figure 5 with the corresponding standard deviation s:

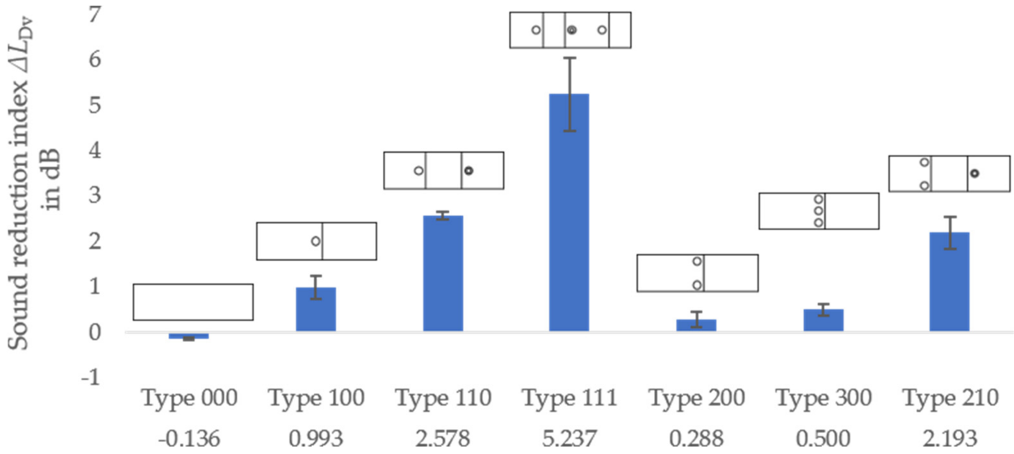

Figure 5. Sound reduction index values averaged across the sample series.

The sound reduction indexes for the different samples differ significantly, see Figure 5. The number and arrangement of the clinch points has a major influence on the damping of the structure-borne sound in the structure. This is a prerequisite for the direct use of the empirical data, which were determined according to the measurement method implemented here. A possible application of the method could be the detection of irregularities by comparing the sound reduction index of a defect-free structure with other manufactured structures in a series. Deviations over the service life of a single structure, caused for example by damage to a single clinch point within the structure, could also be detected. It is unclear how strong the influence of the material and the process parameters is on the differentiability of various structures on the basis of the sound reduction index.

The second aim of the paper is to evaluate whether the superposition principle, modelled on the insertion sound reduction index, is a suitable assumption for a simple analytical model of sound conduction through multiple clinched structures. Equation 2 is used to calculate the insertion sound reduction index ΔL_{DE} of a clinch joint by subtracting the sound reduction index ΔL_{Dv} of sample 000 from the sound reduction index of sample 100:

$$\Delta \mathrm{L}_{DEClinch\ Joint} = \Delta L_{Dv100} - \Delta L_{Dv000} = 1.128 \text{ dB} \tag{4}$$

Equation (4) shows that the insertion of a clinch joint leads to an average reduction of the particle velocity by 1.128 dB. In order to address the research question of this paper (see Figure 2) sound reduction indexes of samples 110 and 111 are calculated using the sound reduction index of sample 000 and the calculated insertion sound reduction index of the clinch joint:

$$\Delta \mathrm{L}_{Dv110calc} = 2\ \Delta L_{DEClinch\ Joint} + \Delta L_{Dv000} = 2.121 \text{ dB} \tag{5}$$

$$\Delta \mathrm{L}_{Dv111calc} = 3\ \Delta L_{DEClinch\ Joint} + \Delta L_{Dv000} = 3.249 \text{ dB} \tag{6}$$

Figure 6 shows that there are large differences between the calculated and measured values for the sound reduction index values. The reduction of the particle velocity level with increasing number of clinch points in series seems to increase exponentially rather than linearly. The presence of a clinch point in the path of the sound wave seems to influence the sound0attenuating effect of following and preceding clinch points. A possible cause could be reflection and interference processes at the clinch points and the associated material interfaces. Additionally, the increased stiffness of the specimens due to an in- creasing number of joints in series could influence the results of the measurement.

For sample types 200 and 300, clinch points were arranged in parallel. Figure 7 shows graphically the change of the sound reduction index value with increasing number of clinch joints in parallel. Figure 6 shows the values for the calculated and measured values of the sound re- duction index. The error bars for the calculated sound reduction index values were calculated using the error propagation law.

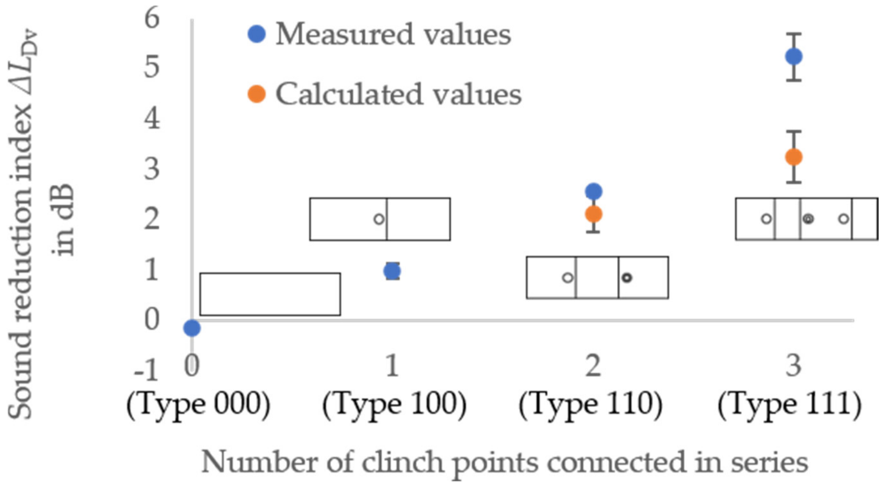

Figure 6. Measured and calculated sound reduction index values for in series clinched samples.

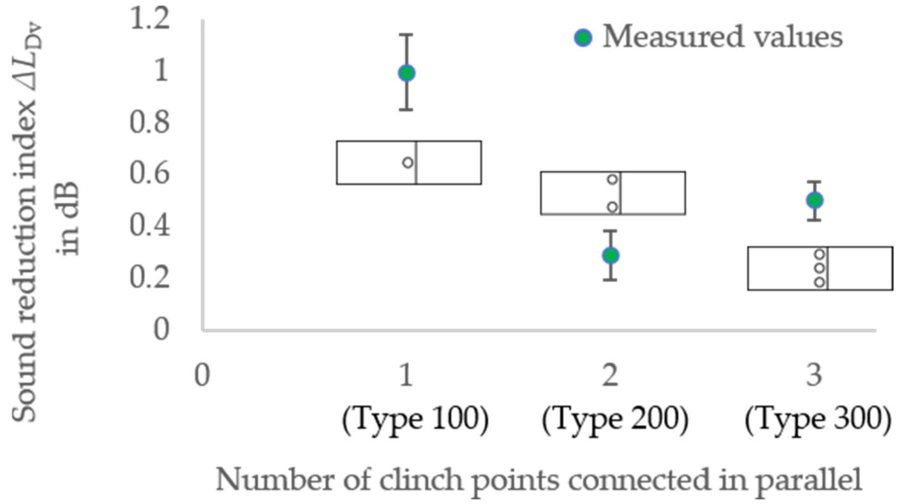

Figure 7. Measured sound reduction index values for in parallel clinched samples.

Figure 7 shows that the sound reduction index value for specimens joined in parallel with several clinch points is lower than for specimen type 100, which represents the joining of the sheets with only one clinch point. The reduced damping over the joint can be explained by a better mechanical coupling of the sheets to each other. The increased damping for specimen type 300 compared to specimen type 200 does not fit this scheme, however, where an even lower damping value from an even better mechanical coupling is expected. It is possible that the effect of the better coupling, which reduces the damping, is compensated by the increase in stiffness of the specimen through the addition of another clinch point.

Another sample was examined with parallel- and series-connected clinch joints. Sample 210 has a measured sound reduction index of 2.193 dB. This value fits the expectations, as it is lower than the sound reduction index of sample 110 with 2.578 dB but higher than the sound reduction index of samples 100 and 200, see Figure 5. For this sample, it is possible to calculate the insulation value according to Equations (5) and (6). First, however, the insertion sound reduction index ΔL_{DE} must be calculated for two parallel clinch joints:

$$\Delta \mathrm{L}_{DE2Clinch\ Joints} = \Delta L_{Dv200} - \Delta L_{D000} = 0.424\ \mathrm{dB} \quad (7)$$

$$\Delta \mathrm{L}_{Dv111calc} = \Delta L_{DEClinch\ Joint} + \Delta L_{D000} + \Delta L_{DE2Clinch\ Joints} = 1.417\ \mathrm{dB} \quad (8)$$

The calculated sound reduction index $\Delta L_{Dv111calc}$ for sample 210 of 1.417 dB is far from the measured sound reduction index $\Delta L_{\mathrm{Dv}210}$ of 2.193, see Figure 5. Additionally, for this sample, the assumption of the superposition principle for sound conduction through clinched joints does not seem to work well.

4. Conclusions

The first aim of this article is to evaluate an experimental measurement method for the sound reduction index of multi-clinched structures. The measurement method based on the two-dimensional measurement of the particle velocity by means of an SLDV achieves reproducible results with a clear differentiability in the sound reduction index values of differently arranged clinch points. A use for the detection of irregularities within a produced series of multiple clinched structures is conceivable. Regular measurements of a single structure could also reveal changes due to damage over the period of use of a structure.

The second aim of the paper is to evaluate whether the superposition principle suggested by the insertion sound reduction index model is a good assumption for sound conduction through multiple clinched sheets. It was found that the damping of the particle velocity increases with the increasing number of clinch points that must be crossed by sound in series. However, there are significant deviations between the measured values and the values of the sound reduction index calculated by superposition. For a triple in-series clinched sample, the measured sound reduction index is 5.237 dB and the calculated sound reduction index is 3.249 dB. This is a relative deviation of 38% from the larger value. The assumption of the superposition principle does not seem to provide sufficiently accurate calculation results for the sound conduction through multiple in series clinched structures.

For sheets that are connected to each other by several parallel clinch points, the sound damping in the joint is significantly reduced compared to a specimen that has only one clinch point. However, if the number of parallel clinch points is increased from two to three, the sound reduction index of the specimen increases again. From this it can be concluded that there are several dominant influences on the sound propagation varying with the number of parallel clinch points. With the data available here, no proposal can be made for a simple analytical model for sound propagation through multiple parallel clinched structures.

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