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ACTIVE VIBRATION CONTROL OF TIMBER FLOORS AND HUMAN-INDUCED EXCITATIONS

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ABSTRACT: Timber offers numerous benefits due to its low self-weight, particularly when used as structural element. However, they also present certain disadvantages in building physics, especially concerning airborne and impact sound insulation issues. One approach to address this challenge is to provide additional mass, particularly in floor constructions. This practice, in turn, compromises the dynamic behaviour in the low-frequency range, which is essential for the serviceability of a slab, and highlights the relevance of related solutions for timber construction. To manipulate the dynamic response of structures is a challenge that can be solved in different ways. The variability of excitation and the randomness of human-induced vibrations concerning time and location placed the focus of the present research on actively controlled systems. It has already been shown that floor vibrations can be actively influenced in a specific manner. Regarding the fundamentals of active vibration control, it is possible to act against undesired vibrations. The research objective presented here is to demonstrate how various active vibration elements can positively influence the vibration characteristics and ensure the comfort, or rather the serviceability, of the floors. The main focus is the performance of these active elements in relation to human-induced excitations.

KEYWORDS: timber structures, active vibration dampers, natural frequency, cross laminated timber, human-induced excitations

1 – INTRODUCTION

The challenges regarding the vibrational behaviour of timber floors have been demonstrated not only via scientific analysis of the design methods but also in research projects with in-situ measurements [1, 2].

Timber structures are mainly distinguished by their low mass relative to their stiffness. However, a certain mass is needed to ensure sound and impact insulation. This presents a challenge in the form of altered dynamic behavior of the floors, particularly regarding low-frequency vibrations caused by human activity. Increasing structural slab thickness is not a reasonable approach in times of increased focus on resource efficiency. In addition, refurbishments, including improvement of serviceability, are another frequent request by practice, with currently limited applicable solutions. Based on the findings from research on point-supported flat slabs, the relevance of improving the vibration characteristics of uniaxial continuously supported systems becomes evident as well. Various publications have already discussed the basics of active vibration reduction [3 - 7].

New systems in the field of active vibration reduction must fulfil certain requirements in terms of dimensions, dynamic forces and a reliable short delay in the reaction. To ensure cost-efficiency, the price per unit and the necessary power consumption have a specific impact on active elements. It should also be possible to control these systems using commercially available equipment. The parties involved in this research are particularly interested in the effects that low-cost equipment of actively controlled systems has on the vibration behaviour of cross laminated timber (CLT) floors.

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This research aims to demonstrate the active counteraction of undesirable excitations with electromagnetic systems, leading to reduced vibration acceleration. Having worked out the basics of active control and based on the results of first tests, the focus is now on systems that are suitable for practical use and can be installed in real structures. Experimental investigations with CLT panels and corresponding floor structures in combination with active vibration reduction will be presented. Appropriate calculation models, which are benchmarked by measurements, should facilitate practical implementation. Furthermore, this paper also compares experimental tests and numerical analysis.

This paper primarily addresses the measurement and calculation of human-induced excitation. It gives a brief insight into previous investigations using shaker systems as actuators (excitation by walking person). The integration of the actuators into the calculation model also relates to the load function according to individual footsteps. However, the comparison of the different actuators is realised with the Heel-Drop tests.

To protect intellectual property, invention disclosures have already been filed for several of the methods presented here in collaboration with our project partners.

2 – MATERIALS AND METHODS

2.1 ACTIVE COUNTERACTION

Actively counteracting undesired vibrations is intended to improve the serviceability of floor systems. To make this possible, a defined mass is accelerated and the resulting dynamic force counteracts the excitation. Fig. 1 shows the basic idea behind active counteraction with human excitation (red - dotted arrow) and counteraction (green - dash-dotted arrow).

The concepts of active control are generally based on acceleration or velocity feedback [3, 9]. When reducing the floor structure to a mass oscillator, both the effective modal mass and the damping can be influenced. According to Eq. 1, the additional force from the active element $F_{ae}(t)$ acts on the system consisting of mass M, damping C and spring stiffness K in addition to the excitation by the person $F_p(t)$.

$$M\,\ddot{x}(t) + C\,\dot{x}(t) + K\,x(t) = F_{\mathrm{p}}(t) + F_{\mathrm{ae}}(t) \qquad (1)$$

All these control strategies aim to reduce the effects resulting from human-induced excitation. An acceptable level of serviceability is necessary, even if the serviceability limit state of natural frequency or vibration acceleration according to standards, such as FprEN 1995-1-1 [10], is not fulfilled.

2.2 EXPERIMENTAL TESTS – EQUIPMENT AND TEST SETUP

The test object refers to a single-span CLT element with flooring consisting of fillings, impact sound insulation boards (ISIB) and mineral floating screed. Tab. 1 shows the layers of the test structure. The span for this test series is 5.80 m.

Table 1: Layers of the CLT floor (test setup)

Layer	Addition	Length (mm)	Width (mm)	Depth (mm)
Screed	cement-bounded	6500	1222	70
ISIB		6500	1222	30
Filling	unbounded	6500	1222	60
CLT element	5-Layer 40/20/40/20/40	7000	1222	160

Various actuators and control concepts are tested in terms of counteraction. Shakers of the type APS 400 and LDS

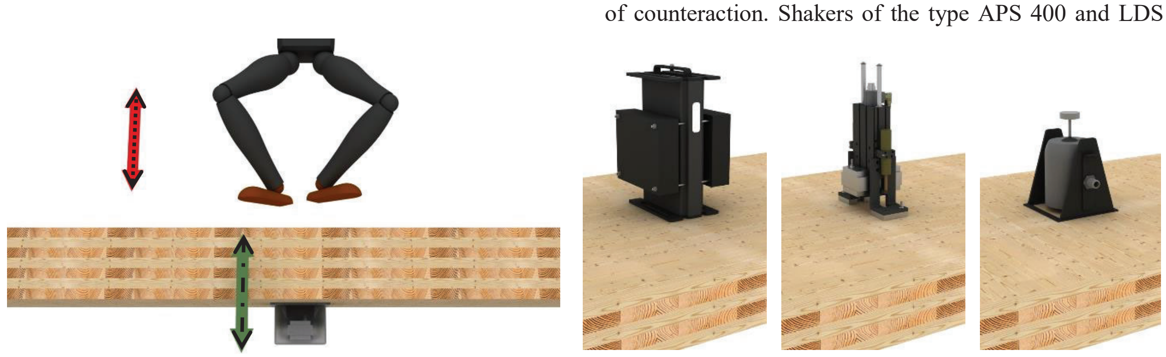

Figure 1: Principle of active counteraction with a future vision of an active counteraction element (left) and actuators to provide the dynamic force (three models on the right) [8]

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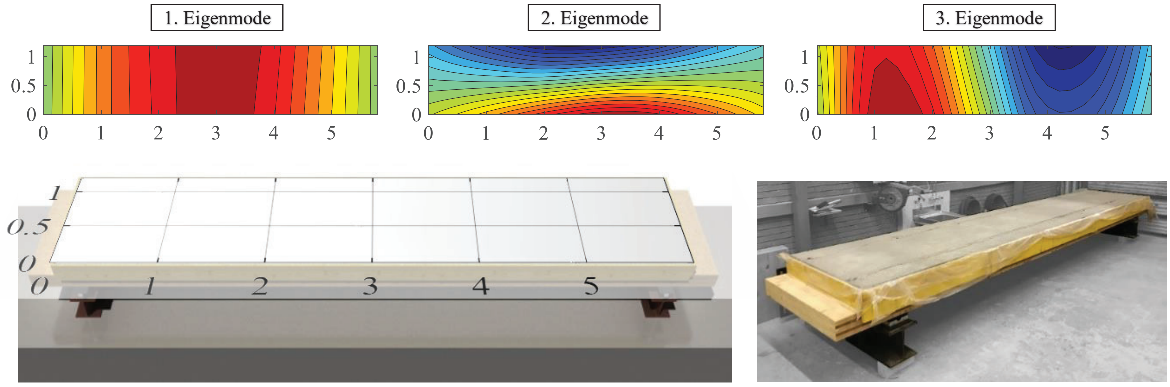

Figure 2: First three Eigenmodes based on the experimental modal analysis of the plate (top), model and specimen of the experimental setup (bottom) [8]

Shaker V400 and electromagnetic linear motors are used as active counteraction unit. Fig. 1 shows all three variants of the active elements used for the tests. However, this work primarily focuses on the tests conducted with the APS shaker and the model based on a linear motor. These models are compared in the tests with human-induced excitation. For comparison, Heel-Drop tests are carried out with the same test person to achieve comparable results.

The dimensions and dynamic properties of the three systems vary considerably. The stroke is between 15 mm and 150 mm. The moving mass ranges between 4.0 kg and 25.0 kg. This results in different frequency ranges for which the actuators can be used. The focus is therefore also on the two aforementioned linear motor and APS variants. The available stroke of these systems allows sufficient dynamic forces to be applied in the low-frequency range. Data acquisition and control are realised on the one hand by equipment from National Instruments such as CompactRIO or rather CompactDAQ and on the other hand by low-cost microcontrollers. Piezoelectric acceleration sensors and capacitive sensors based on micro-electromechanical system (MEMS) technology are used.

In the course of the dynamic investigations, measurements are carried out to determine dynamic parameters such as natural frequencies and modes (Fig. 2). The first three mode shapes are shown according to the natural frequencies f_1 = 7.4 Hz, f_2 = 20.0 Hz and f_3 = 22.0 Hz. A detailed experimental modal analysis enables the system identification of the test setup as well as the determination of the relevant natural frequencies. As part of the research project, the determination of dynamic parameters of different floorings and various support conditions for the present setup also is dealt with (see [11]).

2.3 EXPERIMENTAL TESTS – HUMAN-INDUCED VIBRATIONS

The first experimental investigations on the floor system with active counteraction and the test setup itself can be seen in Fig. 3. The measurements show a significant reduction in vibration acceleration compared due to the human-induced excitation with active counteraction (AVC or On-period). The On- and Off-periods (REF or Off-period) extend over 20 s. The averaged root mean square acceleration (a_{rms}) is calculated in accordance with Eq. 2 over the whole period and also shown in Fig. 4. Based on the results of the investigations with the electromagnetic shaker, which is used for the first tests and the counteraction, investigations on different control and actuator systems follow. The tests are set up such that the active control is always comparable with the reference tests.

$$a_{\mathrm{rms}} = \sqrt{\frac{1}{T}\left(\int_{T_1}^{T_2} (a(t)^2\,\mathrm{d}t)\right)} \tag{2}$$

In addition to the shaker tests, preliminary tests were carried out with a prototype consisting of a linear motor, microcontroller, and capacitive acceleration sensors. The test setup remains the same in terms of floor structure and supports. First results and analyses of the human-induced tests are available. The focus of this paper is on the almost reproducible excitation by the Heel-Drop.

2.4 CALCULATION MODELS

Comparisons between the calculation models and the experimental investigations of excitations by humans are essential for the present work. Via finite element (FE) analysis, the test setup is modeled and the different types

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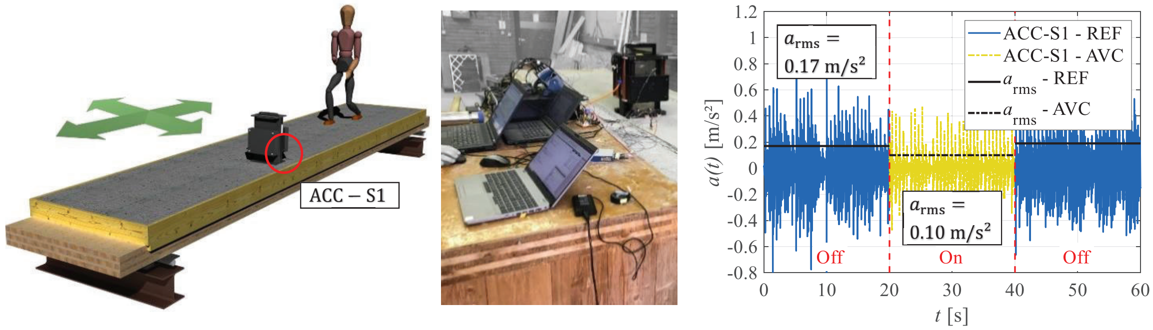

Figure 3. Experimental investigations of human-induced vibrations: setup (left), vibration tests (center) and measurement data (right) [8]

of excitation on the floor structure are investigated. The basis for the models is provided by dynamic parameters determined for the experimental setup. The measured values of the individual configuration phases (structural floor slab, floor with filling, floor with filling and screed) are essential for the validation of the calculation models.

The modelling of human-induced excitation is also crucial for the calculation models. There are different approaches of modelling these time-dependent loads, particularly for forms of movement associated with walking, jumping or running [12, 13]. Like the tests, the modelling is conducted at various stages of the test setup's realisation. The basis for the load functions of the human-induced excitation is provided by existing literature such as [12 - 15], as well as laboratory measurements. The step function shown in Fig. 4 is adapted to the test subjects and the test procedure (weight, step sequence, position, etc.). The simulation background of people walking and further comparison between simulation and experiments is discussed in more detail in [8] and would exceed the scope of this work.

Modelling the excitation caused by a Heel-Drop is less complex in this respect. This can be realised by applying an impulse according to Eq. 3 to Eq. 5. The impulse I_{hd} is calculated from the mass m_p and speed or the height of the Heel-Drop h_{hd}. The force function $F(t)$ is based on a sine half-wave, with values unequal to 0 during the entire impulse duration (between t_0 and t_1).

$$f_{hd} = \frac{1}{2\,t_{hd}} = \frac{1}{2\,(t_1 - t_0)} \tag{3}$$

$$F(t) = \begin{cases} F_{max}\sin(2\,\pi\,f_{hd}\,t) & t_0 \leq t \leq t_1 \\ 0 & t < t_0;\ t > t_1 \end{cases} \tag{4}$$

$$I_{hd} = m_p\sqrt{2\,g\,h_{hd}} = \int_{t_0}^{t_1} F(t)\,\mathrm{d}t \tag{5}$$

This data can be used to analyse the types of excitation in detail. The simulation of human-induced excitations in combination with the actuators for vibration reduction makes it possible to evaluate the functionality of the overall system. The future implementation of the modelled active element enables the dynamic analysis of various floor systems.

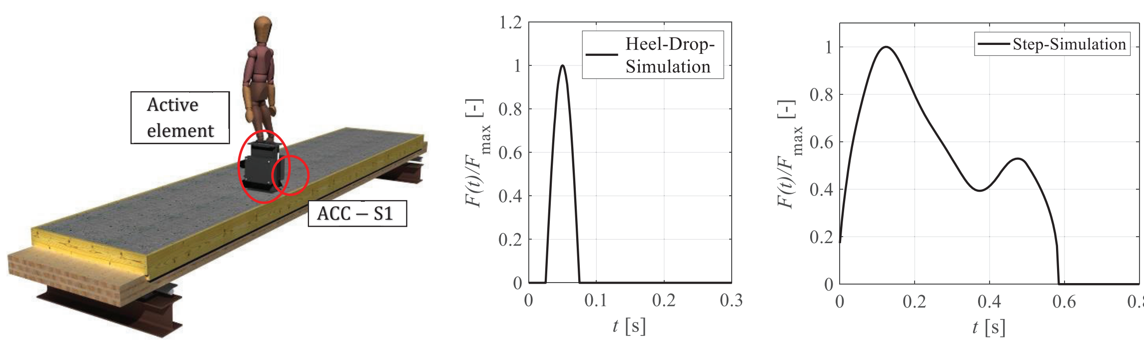

Figure 4: Visualisation of the experimental setup for the Heel-Drop tests and active element (left), force function for the modelled Heel-Drop (center) and force function of a single step for the modelled walking person (right) [8]

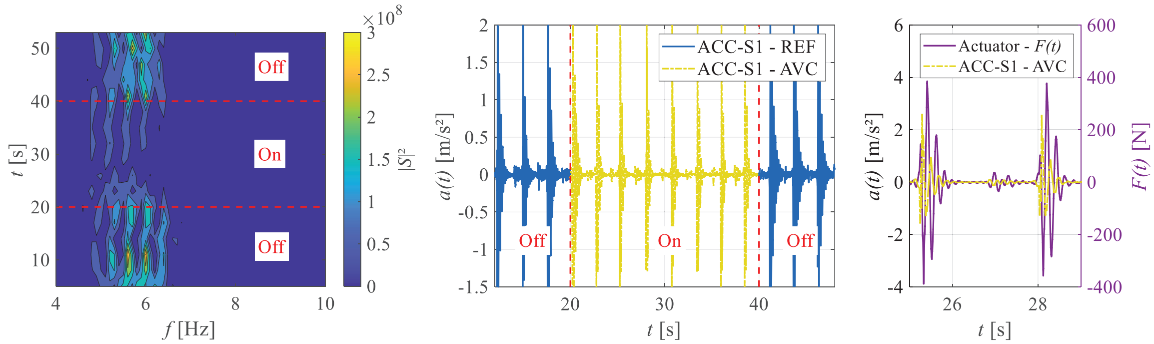

Figure 5: Active reaction in the Heel-Drop tests with the shaker: STFT (left), acceleration in the time domain (center) and dynamic force during two impulse loadings (right)

3 – RESULTS AND DISCUSSION

3.1 COMPARISON BETWEEN DIFFERENT ACTIVE ELEMENTS

The analysis of the test results using active counteraction with shakers, data acquisition modules such as CompactRIO and CompactDAQ and piezoelectric sensors provide very promising results in terms of reducing the vibration acceleration. The setup for the Heel-Drop tests including active counteraction is visualised in Fig. 4. As can be seen in Fig. 5, the reduction is also evident in the visualisation of the magnitudes over the entire measuring range of 60 s using the Short Time Fourier Transformation (STFT). The values in the first natural frequency range are significantly reduced during the On-period. Due to the additional mass of the person and actuator the first natural frequency of this test configuration is lower than indicated in Fig. 2. It is also visible in the time domain that the vibration behaviour after the impulse changes and the accelerations are immediately reduced. The comparison of the applied dynamic force and the acceleration of the CLT floor is also shown. This force is achieved by accelerating the moving mass of 25.0 kg.

The results of the first tests with a linear motor and microcontroller are also available. The acceleration for the evaluation and comparison is recorded using acceleration sensors with a lower sensitivity and higher spectral noise than in the previously mentioned tests with the APS shaker. The unfiltered values are used in the frequency range, which is done using STFT. For the visualisation in the time domain, unfiltered values are available in the relevant frequency range. As shown in Fig. 6, there are also lower magnitudes during the On-period compared to the reference measurement with inactive actuator. Although significantly lower than before, a reduction in acceleration is also noticeable in the time domain. The magnitude of the dynamic force during this test refers to a moving mass of 11.1 kg. Between the visible impulses the reaction is intentionally suspended.

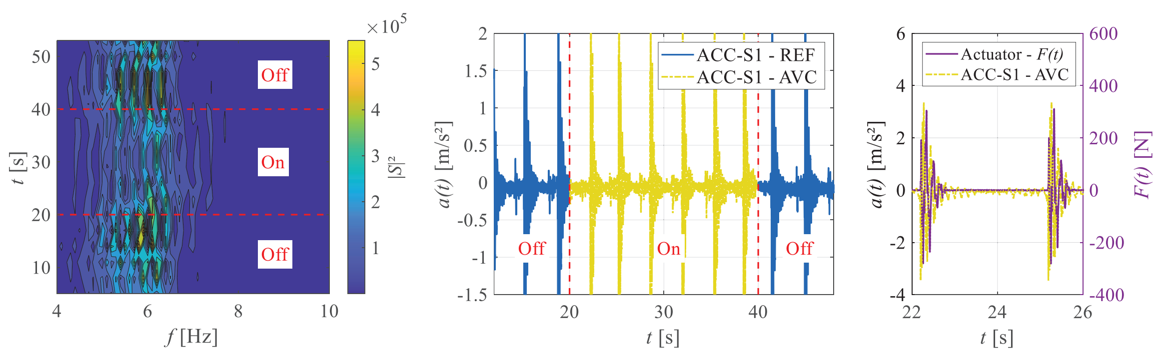

Figure 6: Active reaction in the Heel-Drop tests with the linear motor: STFT (left), acceleration in the time domain (center) and dynamic force during two impulse loadings (right)

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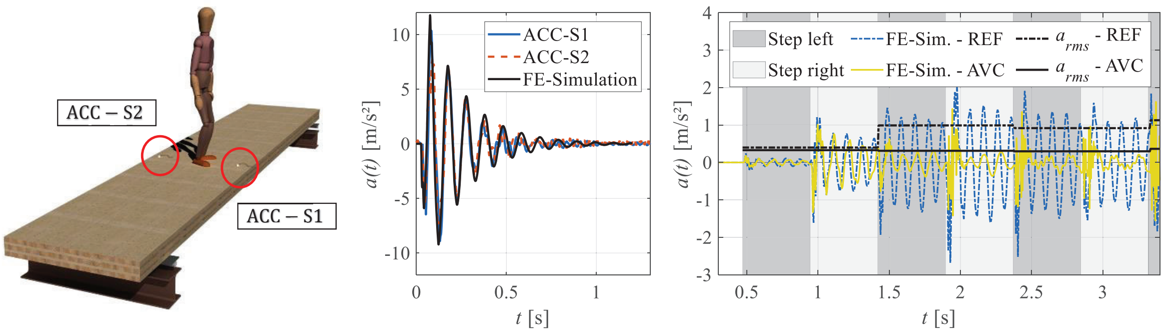

Figure 7: Visualisation of the experimental setup for the Heel-Drop tests and structural floor slab (left), comparison of the measured data with the numerical investigation for the structural floor (center) and comparison of the simulated acceleration between reference system and active controlled system for a structural CLT plate (right)

3.2 COMPARISON BETWEEN EXPERIMENTS AND CALCULATION

An initial approach is being developed to integrate the active vibration elements into the FE simulation. The calculations are performed with the program *SOFiSTiK, Release 2024-1* [16]. The basis for this is provided by both the modal analysis of the test setup and the measurement results from test series with different human-induced excitations.

Fig. 7 compares the Heel-Drop tests of experimental and simulated investigations (evaluation of the preliminary tests with the structural floor slab). The good correlation between simulations and the test results leads to the use of these models for further investigations on the floor slab with flooring as well as simulation with active counteraction. The measured values from the experimental investigations relate to the curves of the acceleration sensors ACC-S1 and ACC-S2. Depending on the normalized force function (see Fig. 4), the associated simulation results are also shown in Fig. 7. The active elements can be simulated in combination with the human-induced load using time history analysis. The modelling of the actuator is currently still independent of the system used. However, the results of the FE simulations show that active elements can be modelled as force function depending on the current dynamic parameters of the slab.

Fig. 7 also shows the simulated data of a walking person on the structural floor slab and single steps over the slab depending on the force function displayed in Fig. 4. Furthermore, the reaction with an active element and acceleration feedback to the first three step sequences is visualised. The test setup is simulated with and without an active element. The reduction due to the integrated active element is also illustrated by the a_{rms} value. This is determined according to Eq. 2 over a time interval of approximately one second respectively one step sequence.

4 – CONCLUSIONS AND OUTLOOK

The tests involving active countermeasures against undesired vibrations (see Fig. 3 and Fig. 5) demonstrate a significant reduction in vibration acceleration. This is also reflected in the effective acceleration value a_{rms}. The

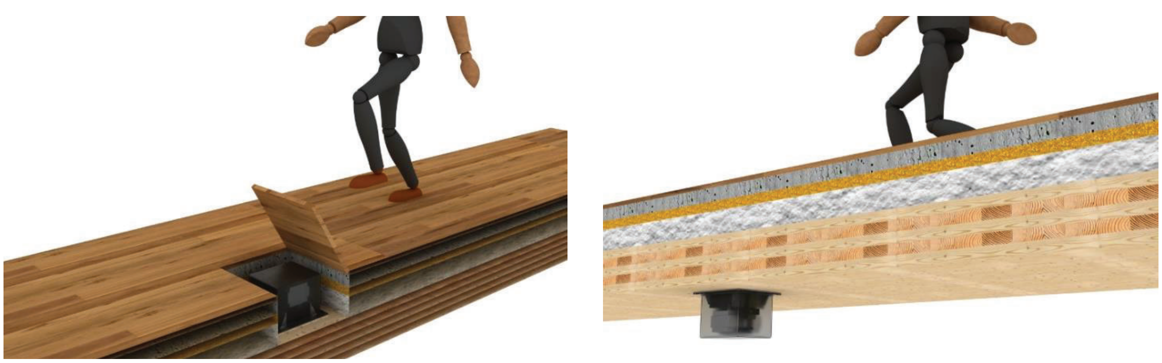

Figure 8: Possibilities of implementation and integration of these active elements on the example of CLT floor elements [8]

modelling enables the integration of the active elements into the calculation program for current and future projects. Developing the model and incorporating the active components into the calculation software presents a considerable challenge because the mechanical model of the active counteraction has to be extended. Additionally, further analyses of complete floor structures are essential.

From the results with the prototype, it can be concluded that the objective of a compact active element can also be achieved with an electromagnetic linear motor. The results in Fig. 6 show that the dynamic force can be applied to the structure at the required times and intensities. This prototype is currently in the test phase and further investigations are planned with regard to its suitability for practical use. Additional measurements of human-induced excitation and comparative measurements with the same acceleration sensors are the aim of the following research. As shown in Fig. 8, possible concepts for the implementation of active elements in floor systems already exist. The prototype will be adapted in the form schematically shown in Fig. 8. Due to the small dimensions, integration into the flooring should be possible.

5 – ACKNOWLEDGEMENT

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