Human induced vibrations of lightweight steel floor systems

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ABSTRACT: Lightweight floor structures supported by cold-formed steel joists have a number of advantages compared to conventional construction methods. Among these advantages are the low weight and the high level of prefabrication. This construction method also allows a short construction time and a very high quality which is due to the weather-independent production in the factory. The weakness of this system may be its dynamic behavior. The research at the Technische Universität Darmstadt investigates the effects of human induced vibrations on lightweight ceiling systems to formulate new approaches to this problem. Experimental investigations in combination with the numerical simulation should develop a dynamically optimized floor structure made of cold-formed steel joists. It is necessary to reduce the dynamic response and increase the damping ratio to get a practice-oriented solution for a broad spectrum of adaptability.

1 INTRODRUCTION

Lightweight steel constructions are in use in several kinds of buildings all around the world. For example there are simply constructed residential buildings, multi-storey buildings, factory buildings, schools and medical centers. It is recognizable that the market share of lightweight steel construction differs between the various countries. To increase the success of the lightweight steel construction industry it is essential to build a high quality product. There are a lot of advantages compared to the conventional construction methods. The additional benefits are the low weight of the construction, the high level of prefabrication, the short construction time, weather-independent prefabrication in the factory, dimensional accuracy, fire protection and the recyclability. In contrast the human induced vibrations and the dynamic behavior are the weakness of lightweight floor systems support by cold-formed steel joists. It is necessary to investigate these effects to be able to formulate new approaches to this problem.

The intention of this research is the development of dynamically optimized ceiling structures made of cold-formed steel C-shaped joists. The numerical model of the dynamic behavior is a differential equation based on matrices of the mass, the damping and the stiffness. The continuous excitation of walking is definable by Fourier series of static force and three harmonic sinus waves verified by preliminary test at our institute. As a general rule the mass is known and so the matrix is recordable. Damping and stiffness depend on many different system parameters. To develop a verifiable numerical simulation it is not adequate to use approximations. All effects of friction and slip as well as potential non linear effects have to be integrated. It was therefore essential to make experiments to assess missing parameters of this orthotropic composite system.

Many design criteria for serviceability use a limitation of mid-span deflection under permanent load. This is equivalent to the minimum natural frequency and is required to eliminate a dynamic response. It does not limit the acceleration and the velocity of human induced floor vibrations. An interesting point to analyze is the low mass of the light weight steel floors in relation to the mass inducing the vibrations. Therefore it is important to define design criteria to upgrade the damping ratio for reduction of the dynamic response behavior. The acceptability of vibrations or the definition of comfort and discomfort is very subjective. It is not possible to prevent the dynamic reaction of a strong impulse induced by a heeldrop or aerobics at lightweight floor structures. These impulses are also recognizable at other structural method for example wide span composite construction or timber floors. But for the excitation through walking it is essential to ensure a high quality standard according to the requirements of every kind of building.

Presented in this paper are the test results of the investigations of the Institute for Steel Structures and Material Mechanics of the Technische Universität Darmstadt which will be the base for following recommendations.

2 EXPERIMENTAL SETUP OF THE LIGHTWEIGHT FLOOR SYSTEM

Lightweight floor systems are used in many different kinds. Floor joists can be made of C-joists or for example as trussed girder. The sheathing can be made of timber, oriented-stranded-board, gypsum board or chipboards. Bridging between the joists, brandering, blocking, the joist support conditions and the type and quantity of connecting devices are only a small range of the possibility of variations. The purpose of the experimental testing was to receive the dynamic reaction close to the reality, the natural frequencies, the mid span deflection, the damping ratio and to find all necessary parameters for the numerical simulation.

Two types of floor systems were built in our testing laboratory. The floor span was defined to 5000 mm as typical span in Germany and a width of 2500 mm to get information on the load sharing. The C-shaped cold-formed steel joists were selected by a steel building system from a local company: SBS-T-20020 C-200 x 40 x 2.0 mm. The first floor was built with 7 single girders and a spacing of 400 mm, the second floor with 5 coupled girders spacing of 600 mm (Figure 1 and 2). Oriented-strand-boards (OSB) with dimension of 2500 mm x 1250 mm x 22 mm were used for the flooring. Between the floor joists and the bearer was a jointed connection. The ultimate limit state was designed by the DASt Richtlinie 016 (1988) and the DIN EN 1993-1-3 (2006). Live load is considered for residential buildings.

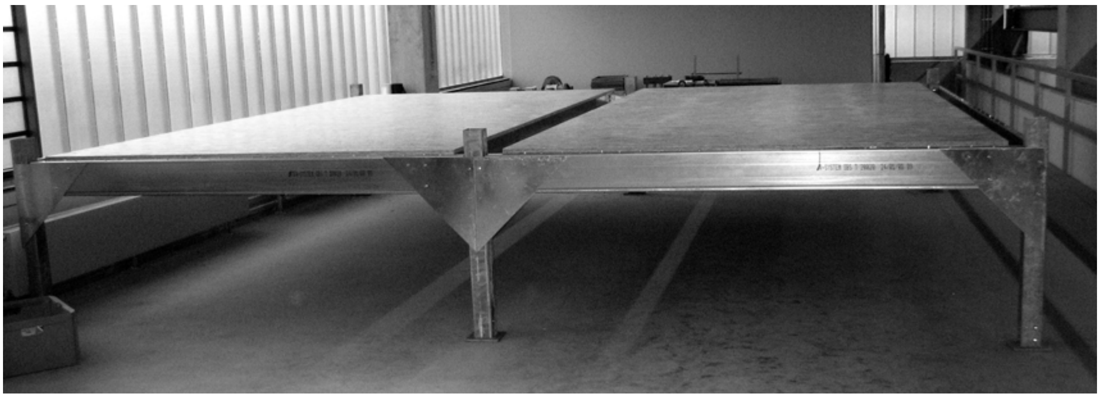

Figure 1. Test floors with C-joists and oriented-strand-board

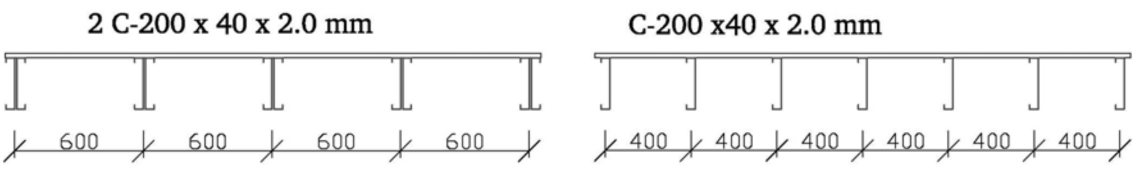

Figure 2. Configuration of the C-joists

The laboratory tests were executed at different stages of finishing investigating and evaluating the vibration behavior of the floor system. All tests were arranged with and without 2 gypsum boards with a thickness of 12.5 mm and a total mass of 20 kg/m² for simulation of the nonstructural components. The orientations of the joints were used to reduce participation. The OSB subflooring was fastened with connecting devices of self-drilling screws Zebra Pias 4.8 x 50 mm with a center distance of 150 mm.

Stages of finishing:

- Oriented strand board (OSB3) 22 mm, optional masses built of 10 sandbags with 25 kg in different arrangements
- Monolithic screed (20 mm expanded polystyrene + 18 mm plaster floor), mass of 22.5 kg/m²
- Dropped ceiling of 12.5 mm gypsum board, brandering on 400 mm spacing
- Simulation of restraining by a cantilever with an evenly distributed dead load of 300 kg
- Changing the connection devices from screws to a ballistic nailing system

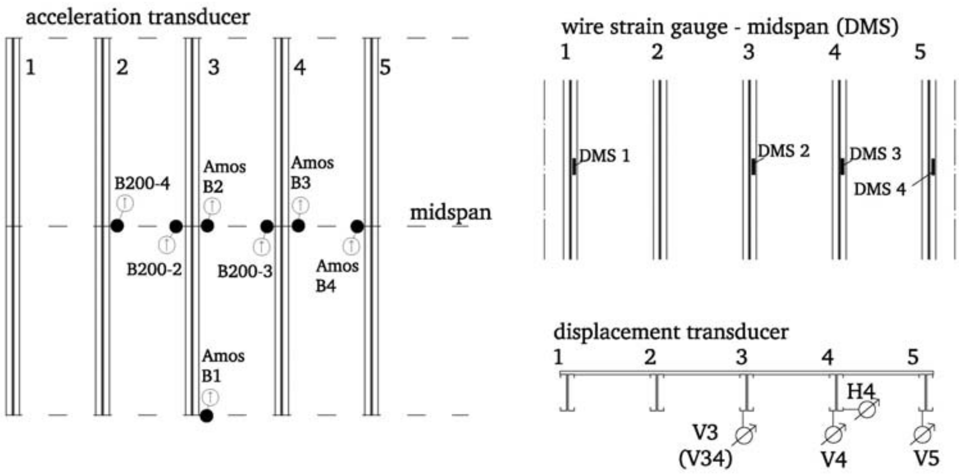

Figure 3. Configuration of the measurement technology

The configuration of the measurement technology (Figure 3) is based on acceleration and deflection. The wire strain gauges were fixed at midspan for plausibility of the high frequent measurement of deflection. 4 displacement transducers to get the information about the deflection were supplemented by a horizontal one fixed at the bottom flange of joist number 4. Two kinds of acceleration transducer were used for different measurement precision. The transducer ‘Amos’ is very sensitive and usable at accelerations lower of 2 m/s² induced by the dynamic load of walking. But heeldrop and sandbagdrop may require a measurement system ‘B200’ for higher amplitudes.

For the numerical simulation it is essential to consider all material properties of the supporting construction with their exact values. In contrast to steel the oriented-strand-board is a very inhomogeneous material. The elastic modulus of bending parallel to the strands is specified in the general technical approval between 3800 N/mm² and 4930 N/mm². We tested the boards with a three point bending test (Figure 4) and received a much higher elastic modulus of 6500 N/mm².

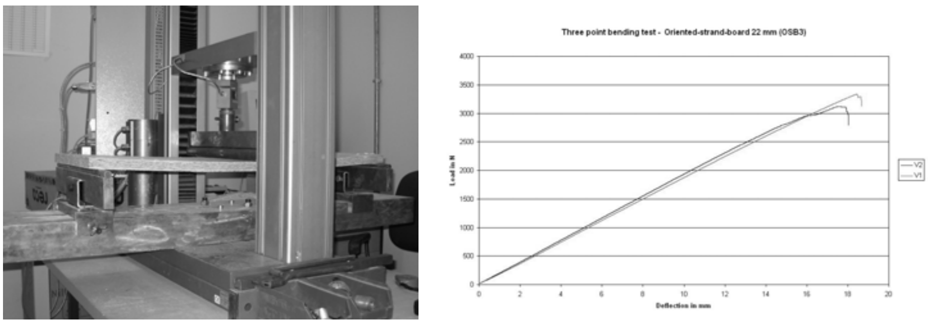

Figure 4. Three point bending test – Oriented-strand-board

3 STATIC AND DYNAMIC LIVE LOADS

The static tests were used to receive a better understanding of the load bearing behavior and the dynamic characteristics. The maximum deflection and the load sharing capacity were ascertained by a single static load of 0.8 kN arranged in midspan. The deflection under a load of 1 kN is one of the guiding parameters in different design codes (e.g. SASFA Code 2007). A comparison with the results is possible by an easy linear conversion. Lightweight floors are a highly orthotropic system. A load of 250 kg evenly distributed in midspan delivers (by the deflection) information on the total stiffness of the composite system of the cold formed steel joists and the oriented-strand-board.

The dynamic tests were arranged by different loads to quantify the vibration characteristic of each system and stage of expansion. The floors were excited by the following loads. All tests were executed five to ten times to eliminate inaccuracies of load and measurement:

- Walking by 2.0 Hz (0.8 kN) – at midspan, parallel and perpendicular to the joists
- Heeldrop (0.8 kN) – at midspan of central and at mid and quarter span of the second joist
- Sandbagdrop (0.1 kN) – at midspan, clear high of 34 cm

All dynamic loads are described in different publications (Bachmann/Ammann, 1987; Wyatt, 1989). Detailed descriptions are given in these papers under consideration of various boundary conditions. But for the numerical simulation of our laboratory test it is essential that we built up the load-time-process near to the reality and the actual size. Therefore preliminary tests of the dynamic loads were performed to record all required values. Figure 5 shows the recorded values of walking with 2.0 Hz. The thin lines describe the load-time-process of every single foot, the thick line the superposition. Bachmann/Ammann (1987) idealize the load of walking by a Fourier series (1) with a constant and 3 harmonic parts (pointed line in Figure 5).

$$F(t) = G \cdot \left(1 + \alpha_1 \cdot \sin(2\pi \cdot f_s \cdot t) + \alpha_2 \cdot \sin(4\pi \cdot f_s \cdot t - \varphi_2) + \alpha_3 \cdot \sin(6\pi \cdot f_s \cdot t - \varphi_3)\right) \quad (1)$$

α_i = 0.4; 0.1; 0.1	Fourier coefficient
φ_i = $\pi/2$	phase displacement
f_s = 2.0 Hz	frequency of walking

The employment of the Fourier series shows excellence accordance to the results of the measurement of walking by the test person. This offers an important approach to the numerical simulation. All calculations are only approximations. A calculation based on time steps can use the measured load-time-gradient. But a harmonical function represented by the Fourier series (1) offers benefits at the modal analysis.

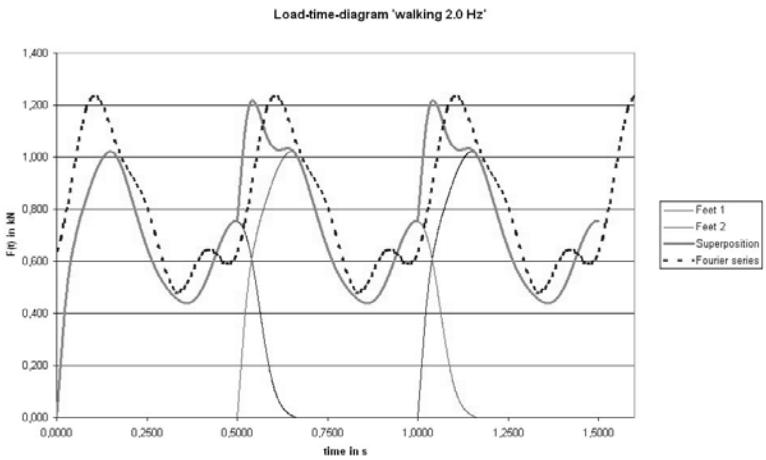

Figure 5. Load-time-diagram ‘walking with 2.0 Hz’

4 NUMERICAL SIMULATION OF DYNAMIC BEHAVIOR

Lightweight floor systems are discrete systems modeled from the components of mass, springs and dampers. The discrete problem is a multi-degree-of-freedom (MDOF) system. The solution is a differential equation (2) based on the acceleration, the velocity, the displacement multiplied by mass, damping and spring stiffness considering external forces.

$$\left[M\right]\left\{\ddot{x}(t)\right\}+\left[C\right]\left\{\dot{x}(t)\right\}+\left[K\right]\left\{x(t)\right\}=\left\{F(t)\right\} \qquad (2)$$

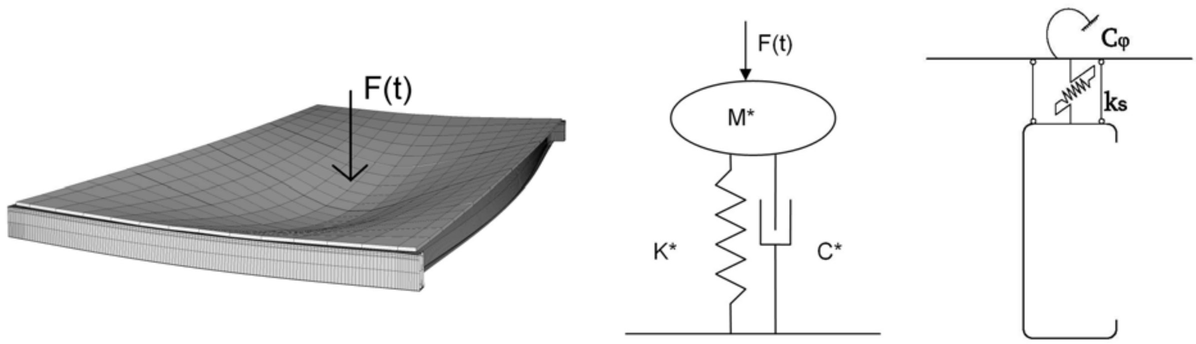

Figure 6. Equivalent static and dynamic system

A single-degree-of-freedom (SDOF) system features only one mass and so the possibility to find a closed numerical solution. MDOF systems are only in some special cases solvable exactly. All solutions are an approximation close to the dynamic behavior. Every result needs a critical verification. The numerical calculations are executed by the software of SOFISTIK based on the time-step-analysis or modal analysis. At the modal analysis it is required to allocate the right natural modes. The floor is modeled using beam and plate elements of the finite element method. They are linked by springs (Figure 6). Experiences with the software have shown that local natural frequencies produced by the modeling bug the calculation. So the preferred method is the time-step-analysis.

The fundamental frequency of a single beam joist with a continuous mass and a constant bending stiffness may be calculated by (3) disregarding the second root term. Lightweight floors exhibit highly orthotropic stiffness ratio. An easy usable equation is not assignable under consideration of all boundary conditions. (3) is a practical approximation. Detailed information are described by Toratti and Talja (2006) or the SCI Publication P354 (2007).

$$f_0=\frac{\pi}{2\cdot l^2}\sqrt{\frac{(EI)_l}{m}}\cdot\sqrt{1+\left[2\cdot\left(\frac{l}{b}\right)^2+\left(\frac{l}{b}\right)^4\right]\cdot\frac{(EI)_b}{(EI)_l}} \qquad a_{w,rms}=\sqrt{\frac{1}{\Delta T}\int_{T_0}^{T_0+\Delta T}a_w(t)^2\,dt} \qquad (3)+(4)$$

5 ACCEPTANCE LIMITS

Many design criteria for serviceability use a limitation of midspan deflection under permanent load. (3) applied to a single-span beam shows that the fundamental frequency depends on $(EI)/(l^4\cdot m)$. This criterion is essential, but it is only a protection against resonance. There is no limitation of acceleration and velocity of human induced floor vibrations. Lightweight structures are tendentious more sensitive then massive structures. The permanent load of a light structure may be less than 100 kg/m². This is a very low value in relation to the vibration inducing mass.

The acceptance limit of floor vibrations is very subjective. ISO 2631-1 (1997) describes that fifty percent of alert, fit persons can just notice a weighted vibration with a peak magnitude of 0.015 m/s². Toratti and Talja (2006) classify residential buildings and offices in vibration classes. So the normal class or base class of the Cat. C inside of one apartment does allow often perceptible vibrations with a maximum acceleration of a_{rms} = 0.075 m/s². The limits differ between various publications. Objective limits may be required by using the floors in commercial building or hospitals.

Some machines do not work correctly under vibrations. So the limits are defined by the technical specifications.

The $a_{w,rms}$ can calculated by (4) using the measured and weighted values $a_w(t)$. The time interval ΔT is significantly involved in this calculation. The recommendation for the interpretation of an impulse is 1 second. But for the comparison of continuous dynamic loads no recommendation of the period length is available. So we determined ΔT to five seconds for the load of walking disregarding of start und end of the vibrations.

6 TEST RESULTS

The laboratory tests display some expected but also unexpected results. The effects of the various construction details on the static and the dynamic behavior are quantified and compared by the deflection, the acceleration, the natural frequencies and the damping ratio.

6.1 *Deflection*

The midspan deflection under a static load is often used as a criterion of the serviceability. Concerning our research it is more important to receive parameters for bending stiffness and load sharing capacity and the integration into the numerical simulation. Figure 7 shows the deformation under a single load of 0.8 kN and different stages of construction. The maximum deflection belongs to the basic system of joists and OSB. The upgrading of the floor with a monolithic screed (connected only by friction) and the dropped ceiling deliver a decrease of the deflection of approximately 17%. This is followed by an increasing of the stiffness and an enhanced load sharing. The additive mass of 20 kg/m² reduces the deflection at the center joist additionally up to 5%. The explanation of this effect can be found by higher shear stiffness between the joists and the OSB due to friction. The primary function of the OSB is the load sharing of the orthotropic system. In this case the bending stiffness is increased by activating composite action. The restraining and the ballistic nailing system do not display a general improvement.

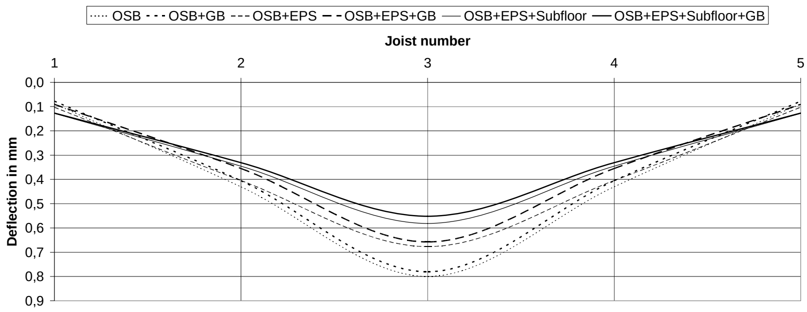

Figure 7. Midspan deflections (load sharing)

6.2 *Natural Frequencies*

The knowledge of the natural frequencies of the floors are essential to avoid dynamic response. All natural modes of a single span girder with a constant shared mass and stiffness can be identified by a number of sinus waves. Lightweight floors are very sensitive and three dimensional systems. Every joist has its own natural modes in translation and rotation. The superposition of these modes delivers a broad spectrum of frequencies. An isolation of natural frequencies can be reached by a Fast Fourier Analysis of measured deflections and accelerations (Figure 8).

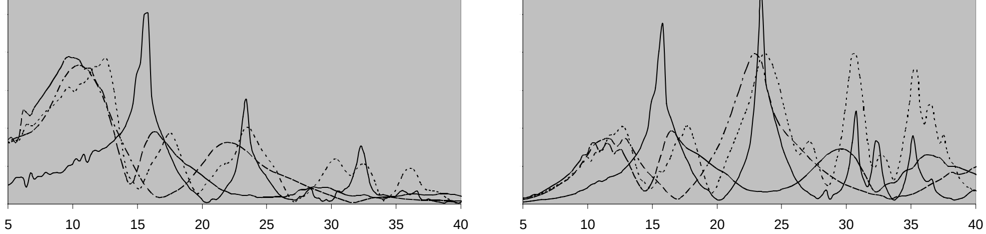

Figure 8. Natural frequencies by Fast Fourier Analysis

Table 1. Results of the Fast Fourier Analysis

Test Nr.	Floor systems	Natural Frequencies (Hz)			
10	C-joists + OSB (screwed)	16,3	23,7		
22	OSB + mass 250 kg (typ 1)	12,1	16,6	29,1	
25	OSB + mass 250 kg (typ 2)	12,2	23,4	30,6	44,2
28	OSB + mass 125 kg (typ 4)	12,5	17,6	23,5	26,5
42	OSB + 20 kg/m²	13,1	20,6	30,4	
56	OSB +monolithic screed (22,5 kg/m²)	13,2	21,8	31,2	48,1
76	OSB + monol. screed + dropped ceiling	12,5	22,8	48,1	
104	(76) + simul. restraining by a cantilever	10,5	11,7	12,9	22,9
109	(104) + 20 kg/m²	9,8	19,9	49,9	
124	OSB + dropped ceiling / ballistic nailing system	14,4	24,6	51,1	

All these results present that there is no dynamic response behavior to estimate. The fundamental mode of the basic system is close to the numerical approximation. The higher natural frequencies are not so easy to isolate in their associated deformation figures. Equal bending stiffness by additional masses decreases the frequencies. But by selective use of additional masses natural modes can be erased or manipulated (table 1 – series no. 10, 25 & 28). Figure 8 displays also the variation of the damping behavior. This shows that the calculation of the dynamic behavior can be only an approximation of the reality to develop optimized systems.

6.3 *Accelerations*

The Comparison of the measured accelerations is based on the $a_{w,rms}$-value (4) analog to ISO 2631-1 (1997) under consideration of a time interval ΔT of 5 seconds. Figure 9 displays on the left side for the center joist and the second joist that increasing the mass and stiffness the accelerations decreases. Adding the dropped ceiling (U) reached a major effect compared to the monolithic screed (V). On the right side of figure 9 the first three values show the modification with the restraining, the last three values the modification from screws to ballistic nailing system with higher shear stiffness. At the deformations there was no recordable effect. At the accelerations we received better results by the system modifications. This shows that under dynamic action the stiffness and the load sharing differ to the static behavior.

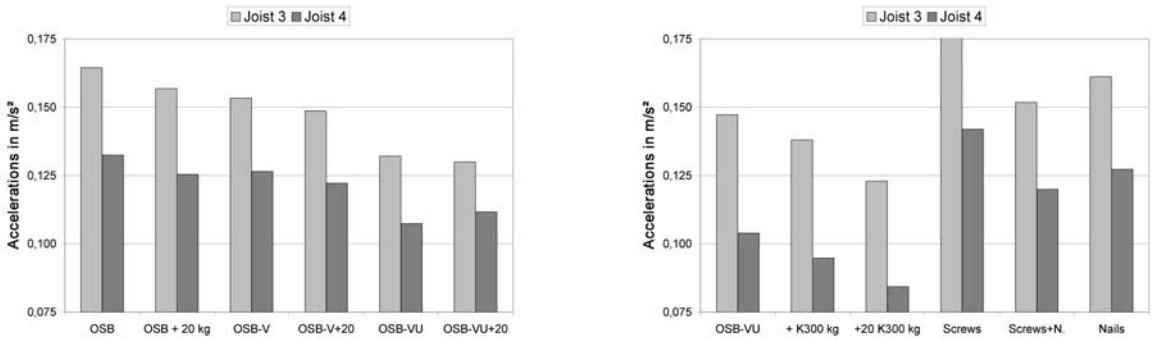

Figure 9. Comparison of accelerations $a_{w,rms}$ of different stages of expansions - 'Walking with 2 Hz'

On-site tests with timber floor constructions with covering reached accelerations marginal lower than the measured accelerations of the lightweight floor supported by cold-formed steel joists. At a concrete floor we have measured accelerations approximately ten times lower. But the dead load of this floor was more then five times higher.

The measured vibrations of lightweight floor systems display that a continuous optimizing is essential and practicable. An approach is to increase the energy absorption by implementation of damping systems and activating of additional masses under using restraining or continuous beams (Neujahr 2003). A disadvantage of continuous beams is that the vibrations are not isolated in one room. The sensation is much higher if the human induced vibrations are generated in neighboring rooms. Another approach is to disarrange the dynamic behavior by various additional elastic separations. Further laboratory tests will be provided and analyzed.

7 SUMMARY AND CONCLUSION

Lightweight steel constructions display an excellent relationship of dead load and load bearing capacity. The weakness of these systems may be their dynamic behavior. Human-induced floor vibrations are describable by a differential equation depending on the vibration mass, the damping ratio, the stiffness and the inducing force. The laboratory tests attempt to indicate the single influence of each of these parameters to optimize the structural design. Massive structures are tendentious less sensitive to dynamic action than lightweight structures. But in order of using the advantages of lightweight floors it is contra productive to increase the mass. Activation of additional masses is only possible by load sharing or continuous floor constructions. A transmission of the vibration to neighboring rooms has to be avoided. The stiffness of the floor joists are decided by the design calculation. Increasing the stiffness will reduce the vibrations. Joists with a higher stiffness as required or joists arranged with a lower spacing have to be related to the economic efficiency. But it makes sense to activate the nonstructural components by upgrading the connectivity to increase the dynamic stiffness. The damping ratio depends on the floor configuration. Energy absorption by implementation of damping systems and structural details is essential to reduce the floor vibrations and accelerate the deactivation of the excited state. Further laboratory tests will be provided and analyzed. The criteria of the fundamental frequencies and the limiting of the dead load and point load deflections are considerable and a first attempt to reduce the vibrations and the dynamic response. But this does not quantify adequate the appearance of acceleration and velocity. Furthermore it is recommended to develop floor details which produce a comfortable floor system. Retrofitting is rarely practicable and most times linked with high follow-up costs. A close teamwork between research, architects and structural engineers is required to establish the lightweight floor structures in a high quality standard for a broad spectrum of use.

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