Assessment of the human comfort of floors based on the use of biodynamic models

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Abstract. This research work aims to investigate the structural dynamic response of steel-concrete composite floors from the point of view of human comfort, when subjected to human walking. This way, the investigated structural model is related to a steel-concrete composite floor building which is composed of a hot-rolled framing system, with a total area equal to 1300m².The floor system is used for normal school occupancy and is supported by steel-concrete composite columns with a ceiling height of 3.40m. The proposed numerical model, developed for the steel-concrete composite floor building dynamic analysis, adopted the usual mesh refinement techniques present in finite element method (FEM) simulations implemented in the ANSYS computational program. In this numerical model, the steel-concrete composite floor girders were represented by three-dimensional beam elements, where flexural and torsion effects are considered. On the other hand, the concrete slab was represented by shell finite elements. Both materials (steel and concrete) have an elastic behavior. The complete interaction between the concrete slab and steel beams was considered in the analysis, i.e., the numerical model coupled all the nodes between the beams and slab, to prevent the occurrence of any slip. Regarding the structural behavior of the connections present in the investigated structural model, the beam-to-beam connections and the beam-to-column connections were considered as rigid joints. Having in mind to determine if the investigated floor framing system satisfies the human comfort criterion for walking vibration, the dynamic structural response of the investigated floor was analysed based on the peak accelerations and RMS values. A numerical study was made of the number of people influence on the slab using a biodynamic model. Then, the modal and forced vibration analysis numerical responses were compared to experimental responses. In addition, all numerical and experimental values were determined and classified according to several human comfort criteria, considering situations of the current design practice.

Keywords: Steel-concrete composite floors, Dynamic structural analysis, Biodynamic Model.

1 Introduction

In the last years, based on the use of slighter and more resistant materials, and having in mind the significant progress of the construction processes, the increase in the building floors structural project's slenderness has been significant. However, these floors are designed as light weight structures with low frequencies and low damping. These facts have generated slender building floors, sensitive to human dynamic excitation, and consequently changed the serviceability and ultimate limit states associated to their design. These facts validate that the structural systems of building floors have low values for vibration natural frequencies. In addition, the design of structural systems with low levels of structural damping is observed, related to the kind of materials used, category of construction, non-structural elements presence, age and construction quality [1,2].

Another important point concerns the multifunctionality that the business market has demanded from current engineering designs, based on the buildings intended use for residential common use spaces, offices and gyms [1], which has contributed to these buildings' floors be more susceptible to excessive vibrations arising, mainly, from human activities, such as: walking, jumping, dancing, rhythmic gymnastics and others, generating disturbances to the user with regard to human comfort [1,2]. This can be explained for the reason that these human activities present excitation frequencies harmonics close to natural frequencies values of most structures, in the range of 4 to 8 Hz [3,4].

In this paper, different modelling strategies were developed, based on the use of isotropic and orthotropic systems and these dynamic responses were evaluated based on comparisons between the values structure natural frequencies, RMS acceleration and maximum transient vibration value (MTVV), obtained via numerical modelling using a biodynamic model and experimental tests. Therefore, this investigation has as its central objective numerical modelling and performance of experimental tests to study the mixed floors (steel-concrete) modal parameters, used for school occupation, with total area of around 1300 m², being supported by mixed pillars with 3.40m of ceiling height. In addition, a human comfort analysis of the structural model was carried out according to procedures established in the American Institute of Steel Construction (AISC) design guide [5].

Free vibration experimental tests were made in the floors by means of excitation from controlled jumps close to floor span middle were performed in order to calibrate the results obtained in the numerical modal analysis with the experimental analysis results. Furthermore, forced vibration numerical and experimental tests were performed with person's walking at a resonance pace (f_p = 2.17 Hz) in order to face assess human comfort based on the limits established in design guides and numerical results. The biodynamic model was used in numerical modelling.

2 Investigated Structural Model

The investigated structural system associated to a steel-concrete composite floor, used for school occupation, with a total area of approximately 1300 m², shown in Fig. 1, corresponds to a typical example referring to the 8th floor of a mixed building (steel-concrete), with sixteen stories, including engine room, keg, water tank bottom and water tank cover. The design is from a real and existing building, which is under construction. The investigated building was designed to be a teaching hospital for a private university in Belo Horizonte/MG, Brazil.

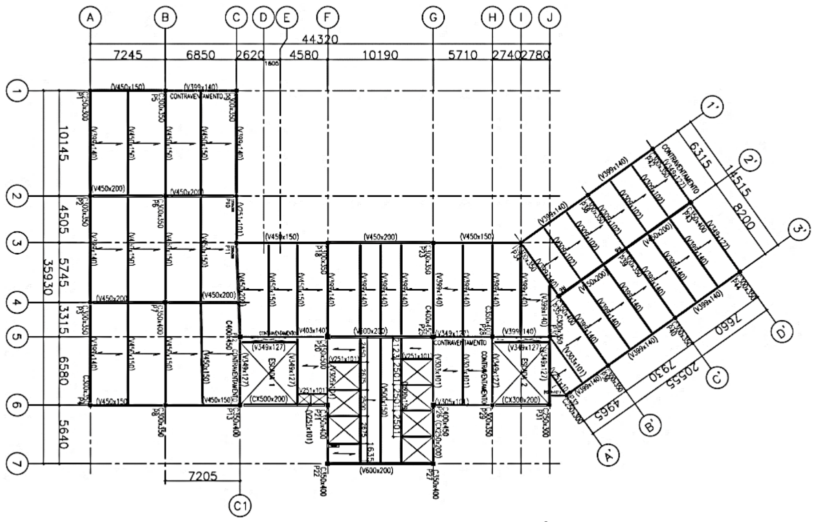


Figure 1. Investigated mixed floor (steel-concrete): 8th floor (dimensions in mm)

The building has a standard height between occupable floors of 3.40 meters. The building pillars and framework structures consists of welded profiles, with geometric dimensions and properties according to design provided by the construction company executing, emphasizing that the pillars are made of welded profiles in the form of a coffin filled with concrete. The slabs are steel deck type with a total thickness of 15 cm, including the MF75 type shape (7.5 cm high) and the shape thickness which, in this design, can assume values of 0.85 or 0.95 mm. It was considered masonry 1.5 meters high around the entire floor, stairwells and elevator boxes, aiming to simulate in a more realistic way the conditions found in the construction at the experimental tests time. It is a structural masonry, built with a 14x19x29 cm structural ceramic block and filled with grout and steel bars, there is also a concrete top beam.

Regarding the materials used physical characteristics, concrete has a characteristic compressive strength (f_{ck}) equal to 300 kgf/cm², an elastic modulus (E_c) of 380000.00 kgf/cm², Poisson's ratio (ν_c) equal to 0.2 and specific weight (γ_c) of 2500.00 kgf/m³; and steel has characteristic yield strength (f_y) of 2531.05 kgf/cm², modulus of elasticity (E_s) of 2039432.40 kgf/cm², Poisson's ratio (ν_s) equal to 0.3 and specific weight (γ_s) of 7849.05 kgf/m³. For structural masonry, a longitudinal elasticity module (E_a) of 203841.27 kgf/cm² was adopted, Poisson's ratio

(ν_a) equal to 0.15 and specific weight (γ_a) of 1250.00 kgf/m³, according to criteria established by ABNT NBR 15812-1: 2010 - Structural Masonry - Ceramic blocks Part 1 [6], in the absence of tests or precise information about block characteristics.

3 Finite Element Modelling

The structural model was analysed using the ANSYS software [7], by the usual discretization techniques associated with the Finite Element Method (FEM). Thus, in the system numerical modelling of steel beams and columns were represented by three-dimensional finite elements BEAM44 [7], where the bending and torsion effects are considered. Steel deck slabs were simulated using finite shell elements. For this simulation the finite shell element SHELL63 [7] was used, which is based on the Thin Plate Theory. The biodynamic components were simulated by a damped single-degree-of-freedom (SDOF) oscillator (i.e., a classic mass-spring-damper), using the element COMBIN40 [7], and the individual biodynamic characteristics used were extracted from studies based on experimental tests by Silva et al. [8].

The complete interaction between the steel deck slabs and the steel beams was considered in the study (i.e., nodes are coupled in order to prevent the occurrence of landslides). The steel and concrete materials are considered to have elastic linear and isotropic behavior, and all sections of the structural model remain flat in the deformed state. The boundary conditions considered restrict as a third-gen support the base and top nodes of the pillars that are half standard height above and below the analysed pavement. The numerical model presents an appropriate refinement degree mesh, in order to allow a good representation of the floor dynamic structural behavior, as illustrated in Fig. 2. It is noteworthy that the beams, columns and slabs have a discretion of 0.25 meters. The SDOF classic mass-spring-damper representation and the chosen floor for experimental analysis is illustrated in Fig. 3.

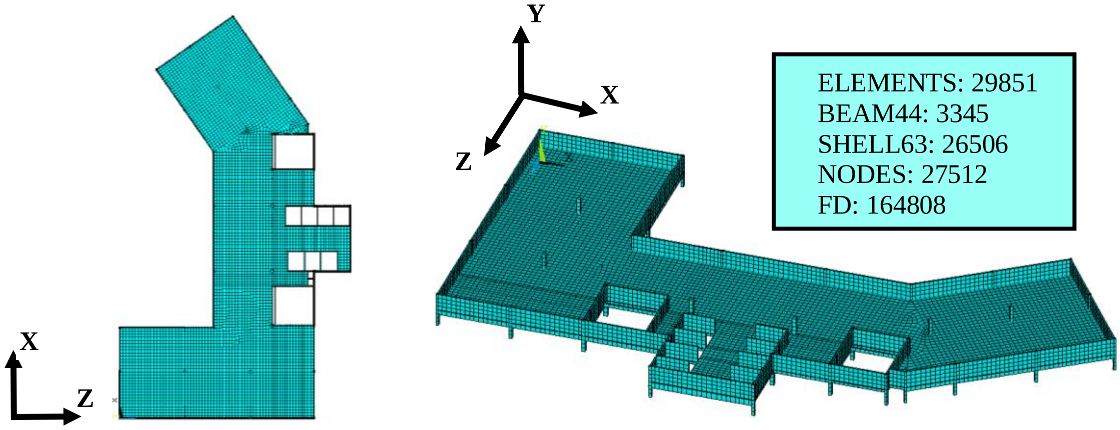


Figure 2. Finite element model of investigated steel-concrete composite floor

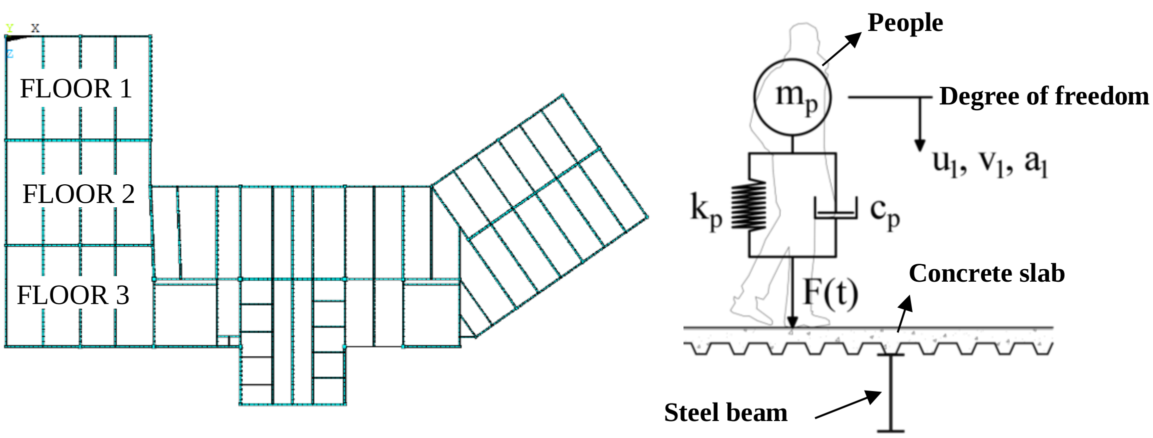


Figure 3. Floors chosen for experimental analysis and the SDOF classic mass-spring-damper

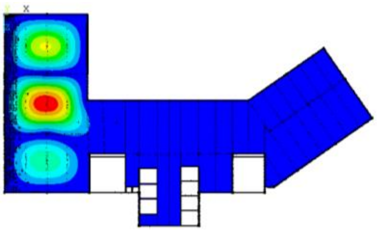
4 Modal analysis: numeric and experimental free vibration

This article topic presents the dynamic structural behavior of the system, based on the calculation of natural frequencies, vibration modes and maximum modal amplitudes. The modal analysis (free vibration) was performed using the ANSYS software [7], where the natural frequencies (eigenvalues) and their respective vibration modes (eigenvectors) were obtained. The influence of biodynamic models increments in the structure is obtained to 1st Floor and 3rd vibration mode. Fig. 4 illustrates the firsts four slab bending vibration modes and the maximum modal amplitudes, and Table 1 presents the natural frequencies values.

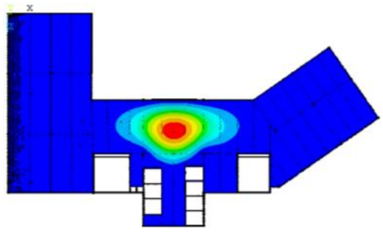
Table 1. Natural frequencies of the investigated structural model

Vibration mode	Frequency (Hz)	Physics Characteristics
1st	5.73	Slab Bending
2nd	6.29	Slab Bending
3rd	6.51	Slab Bending
4th	6.88	Slab Bending
5th	7.29	Slab Bending
6th	7.40	Slab Bending

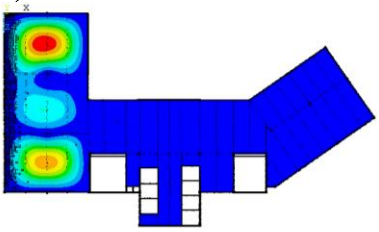
It is worth mentioning that these natural frequencies correspond to vibration modes with maximum modal amplitude on strategic slab panels of the structure (Fig. 3), aiming at comparing the natural frequencies values obtained through finite element modelling and by experimental modal analysis with the criteria established by AISC [5] for human comfort.



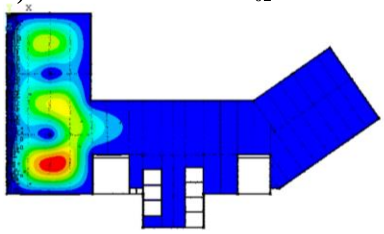
a) 1st vibration mode: f_{01} = 5.73 Hz



b) 2nd vibration mode: f_{02} = 6.29 Hz



c) 3rd vibration mode: f_{03} = 6.51 Hz



d) 4th vibration mode: f_{04} = 6.88 Hz

Figure 4. First four bending vibration modes of the studied floor

The experimental modal analysis was performed through dynamic experimental monitoring, in the place, through the seismic accelerometers installation of the brand PCB Piezotronics, model 393B04, connected to a data acquisition system (brand Bruel and Kjaer, model 3050-A -060), which was connected to a portable computer, responsible for reading and writing the structure response in the time or frequency domain.

The free vibration test was performed in such a way that floors 1, 2 and 3 (Fig. 5) were excited by a 102.6 kg person impact, wearing boots with flexible plastic soles, jumping in their respective floor's centers, at a height of 0.48 m (height of the wooden seat used as a platform). The method used in this test was single input and multiple output data (SIMO).

Fig. 6 presents the experimental results of frequency domain from the readings performed on the structural model, free vibration, in order to identify the eigenvalues that most collaborate with floors selected vibrations for analysis, which are not reported to the transfer power for quick system response. It is important to note that since the impact load of the jump was not measured, it was not possible to obtain the FRF (Frequency Response Function) for each point in this test. However, how floors natural frequencies are identified through the dynamic response FFT (Fast Fourier Transform) of investigated points.

Figure 5. Floors chosen to carry out the experimental tests

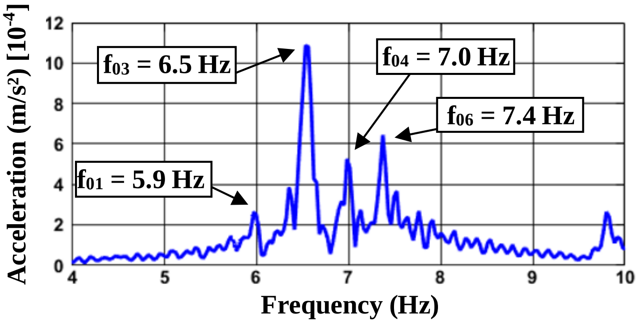


Figure 6. Example of frequency domain response for Floor 1 obtained by experimental measurement

The structure modal damping coefficients for the first six bending modes were obtained by the logarithm decrement method, being, respectively, 1,26% (1st mode), 1,03% (3rd mode) and 1,19% (4th mode). Analysing the same Fig. 6 graph for all floors, it appears that it is possible to identify the peaks of main frequencies corresponding to the five vertical structure vibration modes for the three tests performed. It is observed that the 2nd e 5th vibration mode does not manifest itself in the floors test responses obtained, which was already expected, these modes have a low oscillation range on the floors mentioned, being difficult to differentiate in relation to noise signals.

Based on the presented values in Table 2, it is noted that the experimental results obtained for the three floors have a good agreement with each other, as well as when compared to the numerical results which presents a difference from the numerical result, in relation to experimental response of all floors, above 3 %.

Table 2. Comparison of the natural frequencies: experimental tests and numerical modelling

Mode (See Fig. 4)	Natural Frequencies (Hz)				Difference (%)		
	Numeric Modelling	Experimental test					
		Floor 1	Floor 2	Floor 3	Floor 1	Floor 2	Floor 3
1st	5.73	5.9	5.9	5.9	2.97%	2.97%	2.97%
3rd	6.51	6.5	6.5	6.5	0.15%	0.15%	0.15%
4th	6.88	7.0	6.9	7.0	1.74%	0.29%	1.74%
6th	7.40	7.4	7.4	7.3	0.00%	0.00%	-1,35%

5 Dynamic analysis: numeric forced vibration

The influence of the step frequency, mass ratio and damping ration in dynamic response is investigated. The step frequency (i.e., footfall rate) range was found between 1.5 and 2.5 Hz. The RMS values of acceleration history are illustrated in Fig. 7 for three only force loading methods, using as reference the expressions of Bachmann e Ammann [8], Kerr [9] and AISC [5], and for two using biodynamic modelling methods, moving damped-oscillator loading (MDO) and moving and stationary damped-oscillators (MSDO) models.

In Fig. 7 it can be observed that dynamic response increases significantly when the 3rd harmonic of step frequency is approximately the natural frequency of Floor 1 (f_{03} = 6,5 Hz). The biodynamic models have a reduced dynamic response when compared to only force loading of -22 % and -63 % approximately to MDO and MSDO models. This reduction may be related to additional damping coupled to floor associated to natural frequencies reduction due considering the human-structure interaction (HSI). The RMS values of the acceleration histories were calculated from two loading models: only force (Kerr [9]) and MDO. The comparison is illustrated in Fig. 8 as well as their difference.

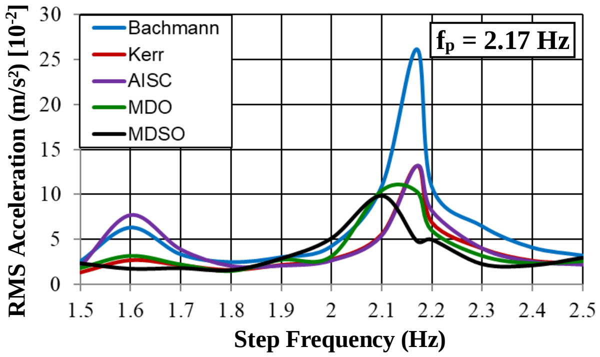


Figure 7. The influence of the step frequency on the dynamic response of floor

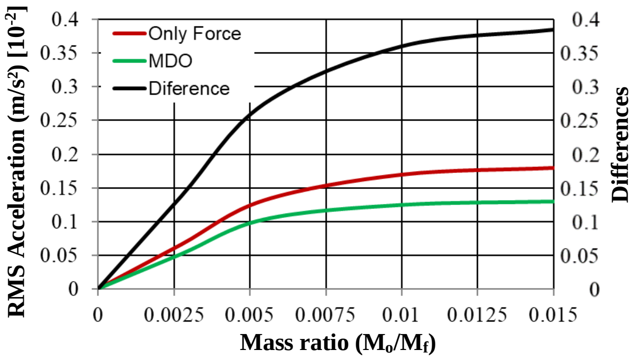
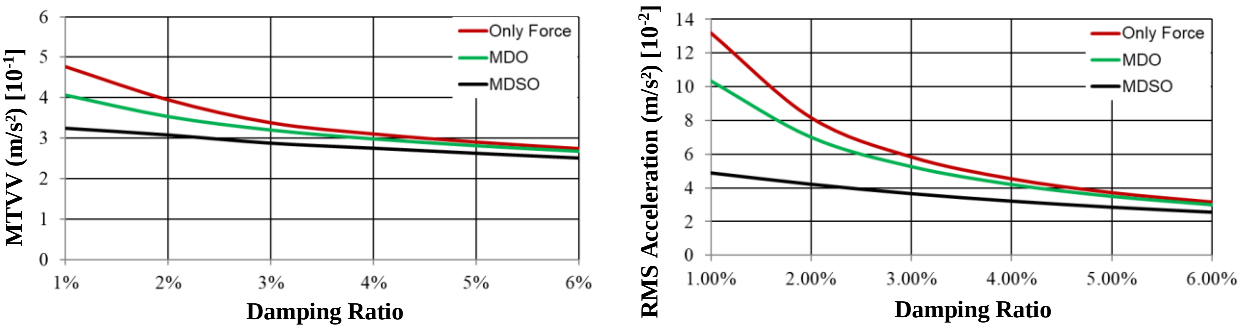


Figure 8. The influence of mass ratio on the dynamic response of floor induced by human walking (M_o - mass of occupants; M_f - mass of the floor)

Based on the results presented in Fig. 8, it can be seen that the differences between the only force models and MDO dynamic response increase with the increasing of the mass ratio, which indicates that the influence of HSI becomes more significant with the increase of the mass ratio of the human occupants compared to the floor. It can be found from Fig. 9 that the RMS accelerations obtained from Only Force model decrease rapidly with the increase of the damping ratio in the range between until 0.02. However, for MDO and MSDO models, the decrease rates are considerably slower when compared to Only Force model.



a) MTVV b) RMS Acceleration

Figure 9. The influence of damping ratio on the dynamic response of floor

6 Human comfort assessment

The dynamic structural response of the steel-concrete composite floor was investigated, when subjected to human walking; having in mind possible discomfort related to excessive vibrations, see Table 3. This way, the peak and RMS acceleration values calculated in the dynamic analysis were compared with the corresponded limits proposed by AISC (a_{lim} = 0.05 m/s² [5]) and ISO-10137 [11] (a_{lim} = 0.005 m/s²), considering the maximum transient vibration values (MTVV) and the RMS acceleration values, respectively. Based on the Table 3 results, it can be verified that for all investigated situations the floor (Floor 1) is considered discomfort to occupation.

Table 3. Human comfort assessment (Floor 1: see Fig. 4 and 5)

Resonance walking (f_p =2.17 Hz)	a_p (steady-state response, m/s²)	Difference Only Force (%)	MTTV (m/s²)	Difference Only Force (%)	RMS (m/s²)	Difference Only Force (%)
Only Force Models	0.185	-	0.4770	-	0.1318	-
MDO (moving damped-oscillator)	0.142	-23.24	0.4060	-14.88	0.1034	-21.55
MSDO (moving and stationary damped-oscillators)	0.090	-51.35	0.3241	-32.05	0.0487	-63.05

7 Conclusions

This research work investigated the dynamic structural response of a steel-concrete composite floor subjected to human walking, based on the use of traditional only force models and biodynamic models, having in mind the assessment of the people-structure dynamic interaction effect and the human comfort. The investigated structural model is related to a composite floor used for school occupation, presenting total area of 1300 m². Thus, the main conclusions of this paper are:

1. The developed finite element model proved to be calibrated in relation to experimental modal analysis data. The differences between numerical model and experimental monitoring were mostly below 3 %.
2. Regarding the investigated floor dynamic response, it was possible to observe a reduction of up to 60% and 50%, considering RMS acceleration and peak acceleration on steady-state response respectively, due to the biodynamic modelling, when compared to the only force models. This fact indicated that the people-structure dynamic interaction effect can be relevant, modifying the structure modal properties.
3. It can be clearly noticed that when the MDO (moving damped-oscillator) and MSDO (moving and stationary damped-oscillators) models are considered in the analysis, the human-structure interaction (HSI) induces lower dynamic structural responses due to the people's additional damping present on the investigated steel-concrete composite floor.

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