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Vibration Characteristics of Shallow Floor Structures

Caractéristiques de vibration des structures de plancher mince

Schwingungseigenschaften gedrungener Deckenkonstruktionen

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SUMMARY

This paper examines the vibration behaviour of shallow floor structures constructed from precast concrete slabs supported on steel beams. A number of floor areas in three buildings were tested to determine their fundamental frequencies. The floors were in different stages of construction, and thus offered the opportunity to identify the effects of different constructional steps. Three floor areas were selected for more comprehensive forced vibration tests and also for examining their response to human actions. This paper presents the results of these tests and takes a detailed look at the test that yielded the largest response to the human loads. Finally, it discusses general serviceability issues.

RESUME

Cet exposé traite du comportement des vibrations de structures de plancher mince construites à partir de dalles en béton préfabriquées posées sur des poutres d'acier. On a effectué des essais sur un certain nombre de surfaces de plancher réparties dans trois bâtiments, afin d'en déterminer les fréquences fondamentales. Les planchers sélectionnés en étaient à différents stades de construction, ce qui a permis d'identifier les effets de chaque étape de la construction. Trois surfaces de plancher ont été choisies pour des essais plus complets de vibration à outrance ainsi que pour examiner leur réaction aux activités humaines. Les résultats ainsi que des questions d'utilité générale sont examinées.

ZUSAMMENFASSUNG

Dieses Referat untersucht das Schwingungsverhalten von gedrungenen Deckenkonstruktionen aus Fertigbetonplatten auf Stahlträgern. Eine Reihe von Deckenbereichen in drei Gebäuden wurde zur Bestimmung ihrer Grundfrequenzen geprüft. Die Decken waren in verschiedenen Baustadien begriffen und boten daher eine ausgezeichnete Gelegenheit, die Auswirkungen von verschiedenen Bauphasen zu ermitteln. Drei Deckenflächen wurden für eingehendere erzwungene Schwingungsprüfungen und für die Untersuchung ihrer Reaktion auf menschliche Einwirkungen ausgewählt. Das Referat beschreibt die Ergebnisse dieser Prüfungen und behandelt im Detail jene, bei der sich die stärkste Reaktion auf menschliche Belastung ergab. Schliesslich werden allgemeine Fragen der Gebrauchstauglichkeit besprochen.

1. INTRODUCTION

The work reported in this paper forms part of a wider investigation into the vibration serviceability limit state for floors. The basic problem being that people walking or running across floors will produce vibrations, which for some floors may prove perceptible or even annoying to other users of the building. If the annoyance is of sufficient severity it may disrupt work or suggest that the structure provides a bad work environment, hence this would be termed a serviceability failure. In the past this has not been a significant problem, but with the trend for longer-span and lightweight floors, the dynamic response of the floors grows increasingly important. It is now necessary for the engineer to consider this point in design; in fact, for some designs, the dynamic behaviour may prove to be a limiting design consideration.

The early analysis methods used by non-specialist UK. designers gave minimum design values for natural frequency. The new Eurocode 3 [1] recommends that *the lowest natural frequency of construction floor should not be lower than 3 cycles/second,* which is somewhat lower than the early recommendations. This limiting frequency criteria will be discussed later. In 1989, a design guide [2] primarily for composite floors was produced, but this needs to be broadened and simplified. At the moment there seems to be no clear consensus view of serviceability under foot fall vibration backed by reliable experimental data. The ultimate aim must be a new comprehensive but simple guide for the designer to ensure his floors are serviceable, including a clear guide on calculating natural frequencies and other limiting parameters.

The investigation reported in this paper examines the vibration behaviour of an example of shallow floor structures or slim floors as they are called in the UK. The concept of shallow floor structures in pre-cast or in-situ concrete, where the supporting steel beam is incorporated within the slab depth, arrived in the UK from Scandinavia in 1990. Early projects designed by Swedish companies incorporating the 'top hat' type of fabrication were joined by another unique Swedish concept marketed as the ThorBeam [3]. At the same time British Steel were studying alternative forms of floor construction in Scandinavia and, following research and development work, have recently launched the concept of slim floor beams built from rolled sections and plate. The benefits of shallow floor structures of this nature derive from the direct costs of reduced building heights and the absence of downstand beams in ceiling voids.

Although British Standard floor loading is 2.5 kN/m^2 it is rare for designs to be based on less than 3.5 kN/m^2 (including 1 kN/m^2 for partitions) and more usually 5 or 6 kN/m^2. The higher loads together with a static deflection criterion of span/360 under imposed load produces floor stiffnesses where dynamic behaviour is unlikely to be critical for normal spans. However, at some load level there will be a transition between the dominance of static deflection and dynamic behaviour as the design criterion.

2. DETAILS OF STRUCTURES TESTED

In July 1992 an opportunity arose to test a large number of floor areas in three buildings which were being constructed. This provided a chance to evaluate the performance of a mixed structure of steel columns, composite steel/concrete ThorBeams and pre-cast hollow core units, all of which were proprietary items arriving from different sources. In addition to measuring the finished structural response, these buildings, being in different stages of construction, offered the opportunity to identify the effects of different constructional steps which converted individual component actions into the complete structure.

The general floor grid for all three buildings was 7.2 m square. The typical floor cross-section incorporates a ThorBeam, fabricated from plate materials, which directly supports pre-cast hollow core units. The design superimposed load in the office areas was 6 kN/m^2. The office floors were 200 mm pre-cast concrete units with C35 structural concrete fill in the beam, and 75 mm topping over the pre-cast concrete units in a strip 1500 mm wide about the centre line of the ThorBeam. Reinforcement was included within the structural topping to guarantee the shear capacity and also to provide restraint into the cores of the hollow core units. Tests were also conducted on the plant rooms which were designed for 7.5kN/m^2 but the results are not presented here.

Restrictions in the length of the paper mean that the investigation cannot be reported fully, hence the paper will focus on the key results and attempt to show the changes encountered during the construction process and how they affect the vibrational behaviour.

3. TEST PROCEDURE

Two types of test were used to determine the dynamic characteristics of the floors. First an impact test, which is simple and quick, was used to establish the fundamental frequency of the floor. Then for three selected floors, forced vibration tests were used to determine all the characteristics of the fundamental modes. For the three floors tested using forced vibrations, further tests were conducted to monitor the vibrations induced by human actions. It should be noted that the floors were not expected to encounter vibration problems, but it was thought that the investigation would provide details for calculations if longer spans or lighter construction were used in the future.

3.1 Impact tests

The basic principle of an impact test, is to cause the floor to vibrate by introducing a single impact and to monitor the ensuing decay. The analysis of the decay of vibrations can provide an accurate measurement of the frequency of the response and on some occasions can be used to estimate damping, although these damping estimates need to be treated with caution as they usually overestimate the true value. For the site tests, a geophone (velocity transducer) was set up in the centre of the floor to monitor response. The floor was subject to an impact produced by one person using the 'heel drop' method. The response was recorded on a computer, and processed using an FFT procedure to produce a power spectrum which could be examined on site to yield the frequency of the response (usually the fundamental frequency of the floor).

3.2 Forced Vibration tests

In order to obtain the best quality data on the characteristics of a floor a forced vibration test is desirable. The forced vibration testing procedure is described in full in [4]. The procedure uses a vibration generator whose frequency can be accurately controlled, and by identifying, and then exciting the fundamental mode, accurate measurements of frequency, damping, stiffness and mode shape can be obtained.

3.3 Vibration from human actions

On each of the three floors subject to forced vibration tests, the response of the floors were recorded as the floor was excited by a series of human actions. The floor response was monitored using an accelerometer set up near the centre of the floor. In all there were six tests on each floor area and the same person was used for each test. These involved walking and then running across the floor, and then at the centre of the floor slow jumping, quick jumping, slow running on the spot and quick running on the spot. The response was recorded for eight seconds and the recording analysed to determine the peak response and the frequency content of the response.

4. BASIC STRUCTURAL CHARACTERISTICS,

Tests were conducted on six levels in three buildings, which included 106 floor areas, four single precast planks and four single ThorBeams.

The four simply supported planks (precast concrete units) gave frequencies ranging from 4.88 to 5.86 Hz and were very lightly damped. The grouting of the planks not only joined them together but also provided a variable connectivity with the secondary steel beams of the framework to provide some two-way spanning action. This was confirmed by taking the mode shape measurement on one area which was in this state. In one case, it was noted that there was no connectivity with the secondary beams and here the measured frequency was 4.88 Hz. Where connectivity with the secondary beams was noted, but where the ThorBeam was not concreted the frequency range was 5.37 to 7.81. Finally when the ThorBeam was concreted the frequencies of the floors ranged from 7.37 to 10.99 Hz.

For calculation purposes, the simply supported beam provides a simple model for calculating the frequency of the precast concrete units. The situation where the ThorBeams are not grouted is more like a simply supported plate, albeit the supports are not rigid, and the completed floor is akin to a plate with two simple and two clamped supports. It is interesting to note that the ratio of frequencies of simply/clamped to simply/simply supported plates is 1.47, and the ratio of the average measured values of the corresponding floors is 1.39. Also if the floor had been designed for a lower imposed load, perhaps 3.5 kN/m^2, and used (say) 150 mm hollow core units rather than 200 mm units, by taking a simple ratio of the design inertia and mass, it suggests that the frequency would be about 0.75 times that of the 200 mm floors.

The above tests results exclude the final finishes, but from experience it can be assumed that, in general terms, the changes which occur with the finishes will follow a reasonably obvious sequence. The false floors will provide increased stiffness and damping, and these increases will be less significant for longer span floors. For areas which have been stiffened by significant structural alterations, adding stairways etc., significant increases in stiffness will result, hence higher frequencies. For areas which have just had a significant increase in supported mass a decrease in frequency will occur. For intermediate cases which have some stiffening and some added mass then only small changes in frequency will result. There will be, however, a general trend for all the damping values to increase, albeit some by only a small amount.

5. MEASUREMENT OF RESPONSE

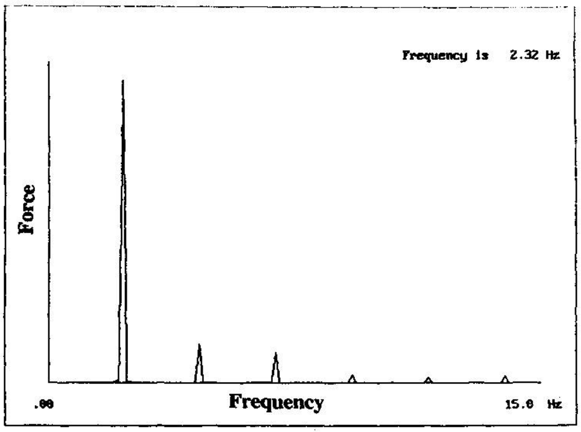
Three floors were subjected to forced vibration tests. Two of the floors were finished and on the other floor (B7) the concrete had not been cast on the ThorBeam. The unfinished floor had a fundamental frequency of 7.21 Hz and damping of 1.44% critical. Of the finished floors C2 had a frequency of 7.92 Hz and 1.69% damping and B2 had two closely spaced modes at 8.23 and 8.71 Hz with approximate damping values of 1.99% and 0.75%. The mode shape measurements on all the floors showed two-way spanning behaviour within the floor area and significant excitation of adjacent floor areas.

The three floor areas were used to obtain measurements of their response to human actions. The peak accelerations are presented in the following table with a note of the dominant frequency of the monitored response. It should be noted that these frequencies are not necessarily the fundamental frequency of the floor. In a number of cases, significant accelerations occurred at several other frequencies besides the dominant one, and for these cases the secondary frequency is given in brackets.

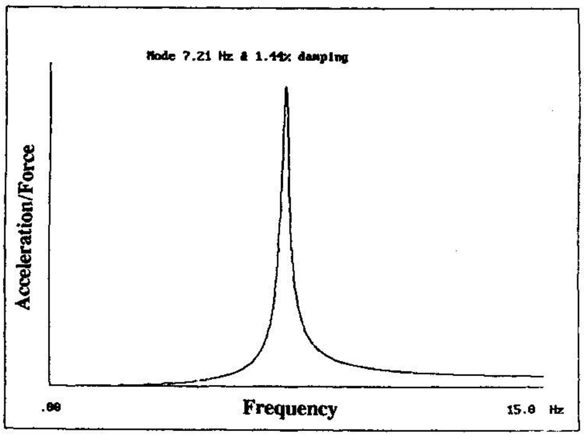
DESCRIPTION	C2 peak accel. g	dominant freq. Hz	B7 peak accel. g	dominant freq. Hz	B2 peak accel. g	dominant freq. Hz
Walking across floor	0.0210	7.93	0.0162	7.81	0.0078	7.69 (8.30)
Running across floor	0.0251	9.77 (8.06)	0.0350	7.20 (7.81)	0.0247	8.79 (6.35)
Jumping on spot (slow)	0.0582	8.18 (7.81)	0.0827	7.08	0.0432	8.79 (7.93)
Jumping (quick)	0.0814	7.57 (9.89)	0.1330	6.96	0.0389	8.06 (5.37)
Running on spot (slow)	0.0234	8.06 (7.81)	0.0190	7.20 (7.45)	0.0123	8.54 (8.06)
Running (quick)	-	-	0.0395	4.52 (7.20)	0.0274	9.79 (4.76)

Examination of the event which produced the biggest accelerations is instructive. The recorded acceleration time history looks remarkably like a single frequency response and indeed the autospectrum shows that the response is almost solely at 6.96 Hz. This is not the resonance frequency of the floor, nor is it the jumping frequency, because there is a upper limit of approximately 3.5 Hz at which people can jump. A closer look at the autospectrum showed another smaller peak at 4.64 Hz and another much smaller peak at 2.32 Hz. What is being observed is responses at multiples of the jump frequency at 2.32 Hz. Examination of the force time history from someone jumping, shows that it is like a series of half sine waves with zero force when the jumper leaves the ground. The frequency content of this time history shows a large force at the jumping frequency and significant but reducing forces at whole multiple values of the jump frequency.

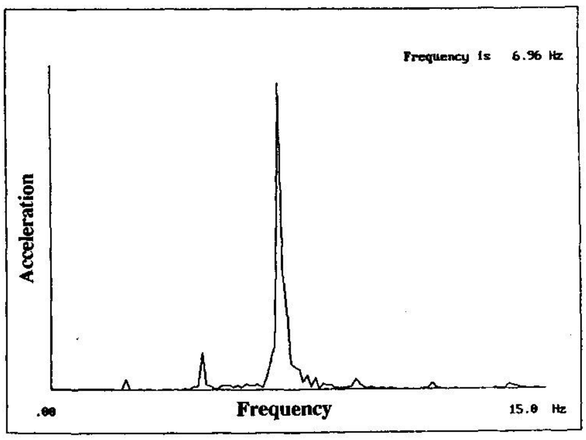
The three adjacent figures illustrate what is happening. The upper figure is a spectrum of the force generated when one person jumps at 2.32 Hz (with a contact ratio of 0.67), and the forces at multiple values of the jumping frequency can be seen. (The frequency resolution of this spectrum is relatively crude but has been selected for compatibility with the lower figure.) The centre figure shows an acceleration transfer function for a one degree of freedom model with a frequency of 7.21 Hz and damping of 1.44% to correspond to the values measured on B7. The structural acceleration is calculated by multiplying the forcing function by the transfer function to obtain a result like that shown in the lower figure. However, the lower figure is the actual spectrum measured on B7 for the response to the quick jumping. At 6.96 Hz only one third of the full resonance amplification is obtained, so if the jumping had been quickened to 2.403Hz then the response could have trebled. This shows the importance of avoiding resonance, and is the reason why a fundamental frequency of more that three times a dancing frequency is often mentioned for dance floors and gymnasia.



Calculated forces for jumping at 2.32 Hz



Acceleration transfer function



Measured Response on B7

The situation for normal serviceability requirements is somewhat different to the dance loads because the normal loads are from walking and running, not jumping. For walking the frequency of pacing is generally between 1.5 and 2.5 Hz and for running this range may extended up to 3.5 Hz; and, as with the jumping, energy can be input at whole number multiples of the basic frequency. The old design recommendations of a minimum floor frequency of 5 to 6Hz, were effectively avoiding the chance of resonance from the energy input at the second multiple of the walking frequency, albeit they were probably just set to be above the walking/running frequency. The EC3 recommendation of a minimum of 3 Hz, could lead to floors where resonance could occur, and therefore produce problems.

Damping is of importance as it controls amplification at the resonance, the amplification being inversely proportional to the damping. It also controls the rate of decay of vibrations following any excitation and this will influence a users perception of the floor acceptability. As it is not possible to calculate damping values, values obtained from tests on similar structures should be used if required.

6. SERVICEABILITY CONSIDERATIONS

There are several national and international guides which give acceptable levels of vibration and the acceptability is influenced greatly by the duration of the vibration. There are also many other factors which are important, but for the purposes of this paper, a simple/rough indication of thresholds is required. The table produced below is extracted from a CEB guide [5], which is stated to be in broad agreement with the values found by many research workers as an indication of human perceptibility thresholds for vertical harmonic vibrations for a person standing.

Description	Freq. range 1-10 Hz peak accn. mm/s^2	Freq. range 1-10 Hz peak accn. g
just perceptible	34	0.0035
clearly perceptible	100	0.010
disturbing/unpleasant	550	0.056
intolerable	1800	0.183

If the measured responses on floor area B7 are compared with the above values it can be seen that the quick jumping on the spot would have produced vibrations of a disturbing/unpleasant nature. However, this isn't really the critical factor, because if someone was jumping at 2.32 Hz by your desk you would be able to see the cause of the vibration and hence not be concerned. The more common criteria would indicate that the running or walking would both be clearly perceptible for the bare floor, but with the addition of false floors and furnishings they are likely to fall into the just perceptible range. Hence the floors tested herein would not have a serviceability problem when completed.

The serviceability problem is technically quite straightforward, because the dynamic characteristics of any floor can be calculated, or approximated, and given a loading function the floors response can be calculated. However, there will be a range of possibilities of load functions with various forces, forcing frequencies and duration's. These will result in a range of accelerations which can be compared with some acceptance criterion. The acceptance criteria are actually quite difficult to establish and depend on many variables, including individual perception, but, as there is quite a lot of information available on the subject, this should be feasible. The easiest way of dealing with the problem, is still to try and avoid it, by designing a floor with a sufficiently high fundamental frequency.

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