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ABSTRACT

Dynamic excitations and the resulting stresses in a weaving mill can affect its functioning in many different ways. Possible consequences of service vibrations include emission of acoustic waves, reduction of product quality, damage of non-structural elements (especially partition walls and cladding) and the disturbance of the activity in buildings placed in close vicinity. It is difficult to identify the influence of the vibrations on the production, on the weaving shed and on the neighborhoods. In 2004, an Italian company has rented in Romania 6000 square meters in a huge, one level industrial building, in order to lay out a weaving mill. Connected to this building there is a small five level office building having 256 square meters in plane. Two categories of weaving looms were installed, air-jet based type and rapier based type. One may say that it was another well-known classical result of the acquisition of second hand equipment. This situation was often encountered in Romania in the last twenty years due to the poor economic situation of the country and to the set up of various private companies which could not afford new equipment. It was not the case, as the Italian company supplied the weaving factory with last generation weaving looms. When the machines started to operate, severe vertical vibrations were generated in the industrial building and annoying acoustical vibrations were induced in the office building, felt especially at the fifth floor. Practically, nobody could stay for more than 10 minutes in any room of that floor. In addition, the high intensity of the vertical vibrations affected the operation of sensitive electronic equipment and, as a result, a business center located at the fifth floor closed its activity. This made the owner lose a big amount of money obtained by renting the spaces. The owner of the building, together with the Italian company, asked R.N.C.E.E.V. to identify the source of the annoying vibrations and to find a technical solution in order to avoid them. As such a case is not frequently encountered and the technical literature is very poor on the subject, the author considers it of interest to be presented. In the paper, the entire process carried out in order to solve this spectacular case of annoying vibrations will be presented.

INTRODUCTION

The object of this paper is the study of severe vibrations that were generated by weaving looms in an industrial building and of the annoying acoustical vibrations that were induced in the adjoining office building. The first complaint of the owner dated October 12, 2004. In the address sent to the Italian company, the owner stated that in the office building there was a high level of noise and excessive tremors which started to damage the walls of the first floor. The second complaint dated April 27, 2005, when the Italian company was notified that the computers of a business center, located at the fourth and fifth floors, were out of order and, more than that, cracks started to appear in the walls. The next complaint, dated June 22, 2005, informed that in three rooms located at the first floor the partitioning walls collapsed and all the business companies had computer malfunctioning problems. The Romanian National Center for Earthquake Engineering and Vibrations (R.N.C.E.E.V.) was employed to solve the problem.

During the first visit at the industrial site it became clear that the work would not be an easy one. The investigation team led by the author of this paper established, first of all, that a complex program of instrumental investigations appeared to be necessary in order to identify, if possible, which type of the weaving looms was responsible for generating the annoying acoustical vibrations. Using Kinemetrics vibration equipment, the rapier weaving loom type was found responsible for the permanent acoustical vibrations in the office building. The next step was to establish a solution for avoiding the vibration problems. To accomplish the task, the technical assessment of the “source” (the rapier type weaving looms) and of the “system” (consisting of the two buildings) became necessary, in order to establish the best solution for minimizing the cost of the intervention.

SOME INFORMATION OF INTEREST RELATED TO THE TWO BUILDINGS

The *weaving shed* is of rectangular shape in plane, consisting of four spans of 18 m and seven bays of 12 m. No partition walls existed in the rented area. Between the two buildings there is a small “*connecting body*” (Fig. 1).

Fig. 1. General view of the complex of three buildings.

As the building concrete floor was not in good condition, the Italian company decided to cast-in-place a 15 cm reinforced concrete plate above the 22.5 cm existing one (Fig. 2). Thus was made an error which consisted of the inclusion of all bases of the columns in the new reinforced concrete plate. In this way, a massive flat plate, like a general “mat” (37.5 cm thick) was obtained. More information will be given later. All the other structural elements of the industrial building were precast type. 44 air-jet and 17 rapier type weaving looms were installed on the new concrete plate, each of these having their own system of vibration isolation.

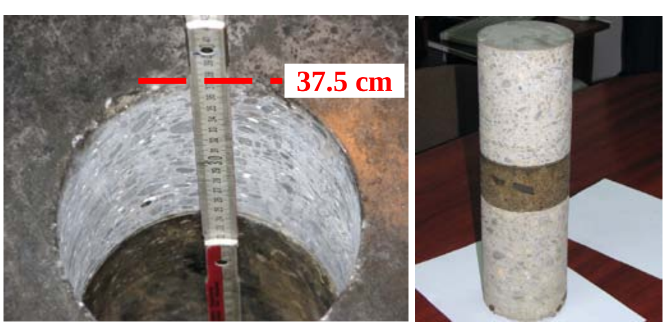


Fig. 2. Boring and core sample.

The *office building* is of square shape in plane, consisting of three spans and three bays, 5.40 m each. From the architectural point of view the building has 5 levels (no basement). The first floor is 4.00 m high, the next three levels are 3.30 m high and the last one is 3.70 m high. The structural system of the building is of reinforced concrete moment resisting frame type. The cross section of the exterior columns is 0.5 m x 0.5 m, while the ones of the interior columns are: first floor (0.55 m x 0.55 m), second floor (0.50 m x 0.50 m), third floor (0.45 m x 0.45 m) and the last two floors (0.35 m x 0.35 m). The thickness of the reinforced concrete slabs is 0.14 m, except that of the flat roof which is 0.12 m. In Fig. 3 the horizontal plane section of the industrial complex which is subject of the present paper is presented. Fig. 4 shows a general view of the rapier type weaving looms.

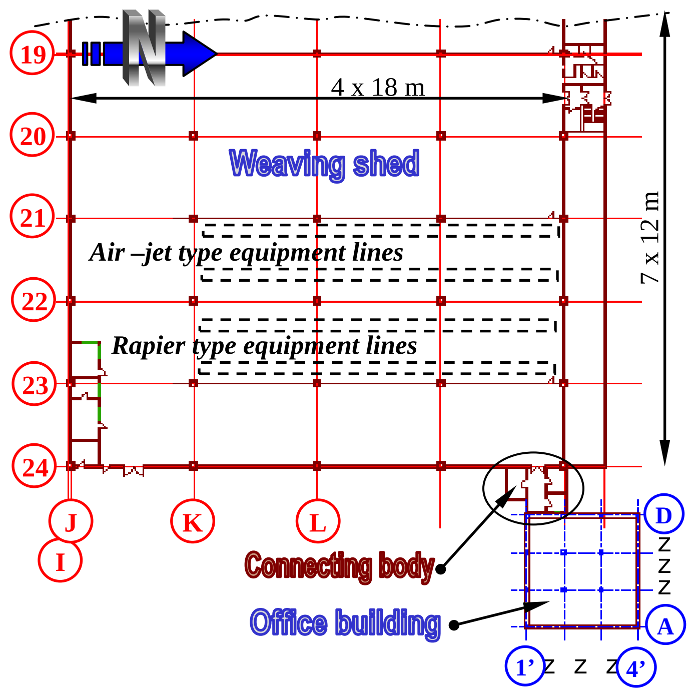


Fig. 3. Overall layout of the industrial and office buildings.

Fig. 4. General view of the rapier type weaving looms.

GEOTECHNICAL STUDY

Another aspect that needs to be revealed refers to the site and ground foundation conditions. It has become recognized that the local site conditions have a very important influence on the response of the structures. The soil and the rocks at a site have specific characteristics that can significantly amplify the incoming earthquake waves traveling from the earthquake focus. The foundation ground in the area where the two buildings in discussion were built can be considered as macroporous weakly cemented soil (loess). Such soil is characterized by a reduced compressibility in dry conditions and by a high sensitivity at wetting with the increase of settlement under constant vertical pressure. In order to establish the lithologic "*column*" of the ground and to determine the main soil characteristics, a geotechnical study was performed in 1969. Starting from the ground level towards the bottom, the position of different subsoil-layers was as follows:

- I – silty clayey vegetable layer, dark-brownish with grassy roots (0.00 ÷ 0.50 m);
- II – loessial silty clay, yellowish-brown, with grassy roots and macropores and calcareous concretions, dry consistent plastic (0.50 m ÷ 2.00 m);
- III – wet loessial clayey silt (2.00 m ÷ 3.20 m);
- IV – silty fine sand, yellowish, medium dense, very wet (3.20 m ÷ 4.55 m);
- V – yellow fine sand, cohesionless, homogeneous, medium dense, saturated.

The ground water level was not intercepted. It is also important to notice that a large part of the site needed to be filled with soil. Where the filling of discontinuity exceeded 1.50 m in thickness drilled plain concrete piles were used for ground improvement.

The foundation level for the industrial building columns was established at about -3.00 m depth from the ground level, in the wet loessial clayey silt; an allowable pressure for the fundamental loads equal to 170 kPa was considered in the structural analysis.

The foundation level for the office building was established at -4.95 m depth from the ground level, at the superior part of the yellow fine sand, cohesionless, homogenous, medium dense, saturated stratum. According to the initial project, the foundation structure of the office building was placed between -1.40 m and -4.95 m depth. The columns of the building reached -1.40 m depth. At this level they rested on some reinforced concrete "*inverted*" beams having 2.55 m height (their flanges were 0.45 m high). These beams rested on a plain concrete general mat of 1.0 m height (between -3.95 m and -4.95 m depth). Under the exterior walls, as well as under the partitioning ones, plain concrete continuous foundations existed between -0.20 m and -2.45 m depth. These foundations also rested on "*T*" shape *inverted* foundation beams of 1.50 m height (in which the 0.45 m flange thickness was included). In the staircase zone, under a wall, another plain concrete continuous foundation was provided, between the levels -0.20 m and -3.50 m.

Considering the above-mentioned characteristics of the supporting ground and the initial structure of foundation, one can state that this could have accomplished the two necessary general requirements for a structure of foundation, as follows:

- the function of "*receiving*" from the superstructure of the structural system the gravity loads and the loads generated by the incidence of an earthquake;
- the function of "*transferring*" the loads received to the foundation ground.

In 1974 the office building structure of foundation was completely modified and, for each column, an isolated foundation was built. Due to the lack of the foundation beams, each isolated foundation had an independent behavior under dynamic actions.

INSTRUMENTAL INVESTIGATIONS

The acquisition of the instrumental data was achieved with highly sensitive modern equipment, consisting of twelve SS-1 Ranger seismometers, widely recognized as excellent short-period field instruments and a VSS-3000, a fully portable acquisition system, designed for ambient and forced vibration field measurements (Kinemetrics).

The first step when performing experimental investigations is to select the locations where motions will be recorded.

The number of measuring points will depend on the type and complexity of the experiment and on the type of the structure. In the present case there were two different buildings, each of them having its own structural system.

More than that, severe vibrations were produced in both buildings with the consequences already presented. The instrumental investigations were carried out in two stages, in June, 2006 and June, 2007.

The first stage

In order to identify the source of the annoying vibrations, several configurations for the positioning of the pick-ups were adopted: 5 arrangements in the industrial building and 4 in the office building.

(a) The industrial building

First configuration (Fig. 5). 12 SS-1 Ranger seismometers were placed in four locations, two of these in the area of the air-jet type weaving looms, and the other two in the area of the rapier type weaving looms. The selection of the four locations was decided according to the workers' statements that confirmed that at these points the vibrations were strongly felt. Three sensors were placed in each location, in order to record the vibrations on the longitudinal, transversal and vertical directions. The *vibration sources* considered were the ambient vibrations and then the starting, operation and stopping, under normal working conditions of the weaving looms.

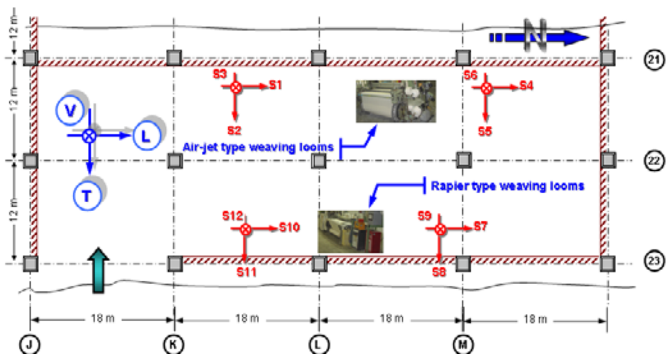


Fig. 5. Weaving shed. Location of sensors (first configuration).

Second configuration (Fig. 6). 6 SS-1 Ranger seismometers were placed in two locations in the rapier type weaving looms area. The *sources of vibrations* were the ambient vibrations, cumulated with the normal operation of the rapier type weaving looms and of the air-jet type weaving looms, considered separately.

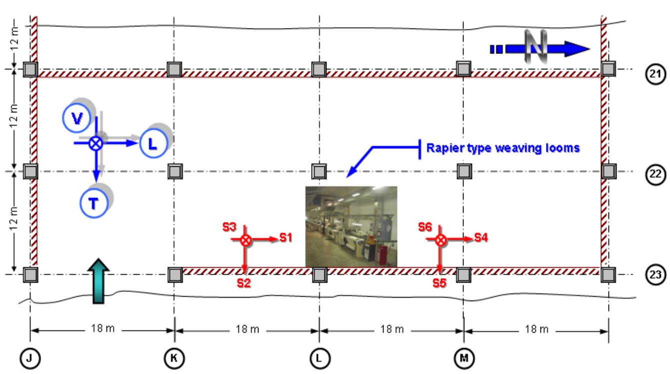


Fig. 6. Weaving shed. Location of sensors (second configuration).

Third configuration. 4 SS-1 Ranger seismometers were placed in four locations on the flat roof of the industrial building, which corresponded to the weaving looms area with severe vibrations. There were performed three sets of measurements, one for each direction.

The *sources of vibrations* were the ambient vibrations cumulated with the normal operation of the rapier type weaving looms, then ambient vibrations cumulated with the normal operation of the air-jet weaving looms and, finally, ambient vibrations together with the normal simultaneous operation of the both types of weaving looms (Fig. 7).

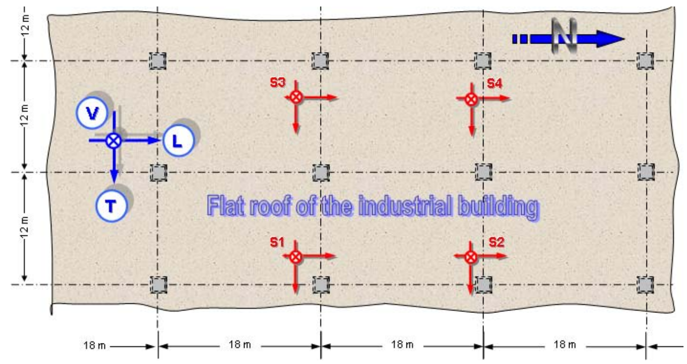


Fig. 7. Weaving shed. Location of sensors (third configuration).

Fourth configuration. 4 SS-1 Ranger seismometers were placed in four locations on the flat roof of the industrial building, in the area of the existing small "*connecting body*" between the two buildings (the industrial one and the office one). Two sets of measurements were performed, one for the transversal direction and one for the longitudinal direction, considering the same sources of vibration as in the previous case (Fig. 8).

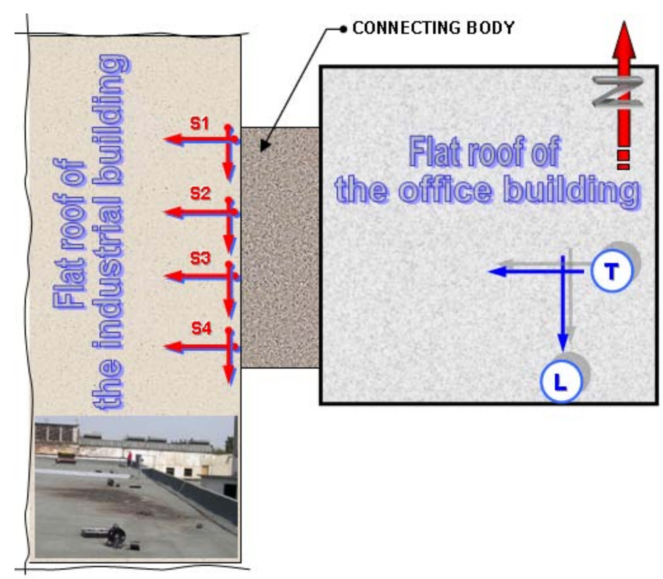


Fig. 8. Weaving shed. Location of sensors (fourth configuration).

Fifth configuration. 4 SS-1 Ranger seismometers were placed in four locations on the flat roof of the industrial building, in the area of the existing "*ventilating pipe*" (Fig. 9). In this case, the sources of vibrations were the ambient vibrations together with the normal operation of all weaving looms.

(b) The office building

The first three configurations consisted in 4 SS-1 Ranger seismometers placed in four locations on the flat roof of the office building. All sensors were oriented, in turn, on the longitudinal, transversal and vertical directions.

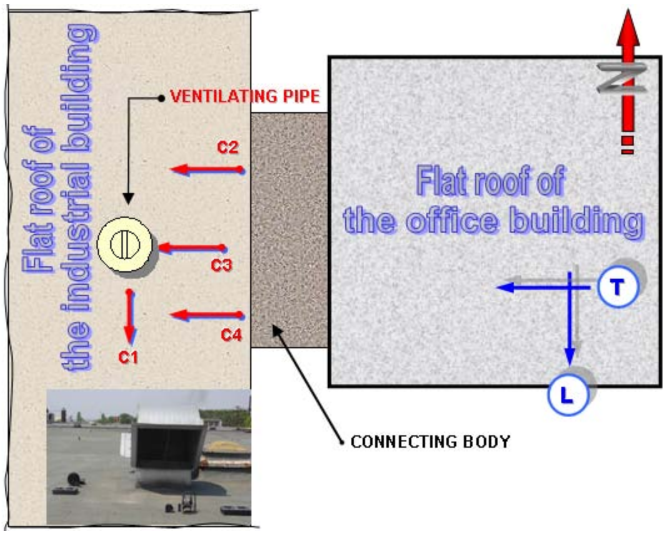


Fig. 9. Weaving shed. Location of sensors (fifth configuration).

The sources of vibrations were the ambient vibrations together with the normal operation of all weaving looms (Fig. 10).

The fourth configuration consisted of 3 SS-1 Ranger seismometers placed in the middle of the flat roof of the office building: two on the horizontal directions and one on the vertical one.

Three sets of measurements were performed considering the following *sources of vibrations*: the ambient vibrations cumulated with the normal operation of the rapier type weaving looms, then ambient vibrations cumulated with the normal operation of the air-jet weaving looms and, finally, ambient vibrations together with the normal simultaneous operation of the both types of weaving looms.

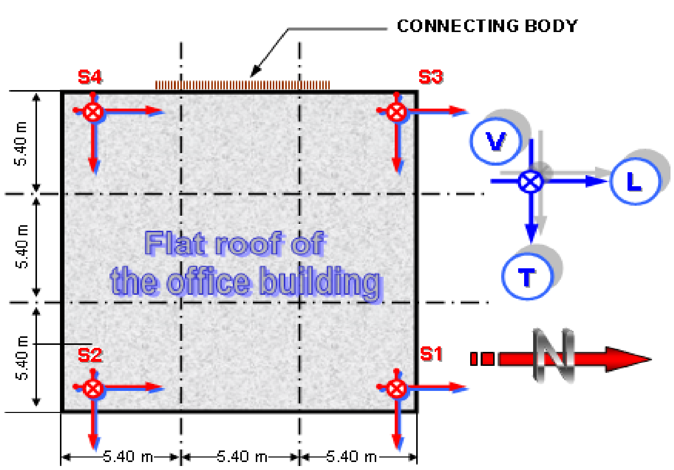
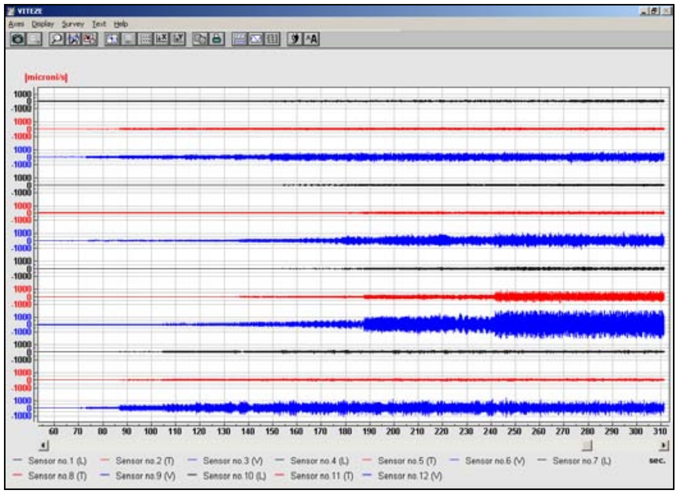


Fig. 10. Office building. Location of sensors.

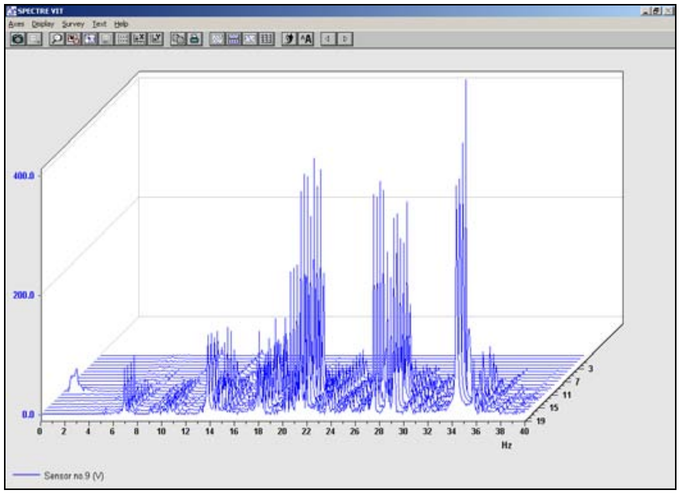
In all instrumented locations *velocities* were recorded. The signal analysis was carried out with specialized programs, the following typical types of analysis having been carried out:

- numerical integration in time domain, obtaining in this manner from the basic signal (velocities) the vibration displacements;
- Fast Fourier Transform (FFT) of the real signal, both for velocities and displacements (Fourier Amplitude Spectra);
- auto-correlation functions, by means of which it is possible to detect an inherent periodicity in the signal itself and to determine the damping ratio;
- calculation of maximum displacement values in the selected measurement locations.

Samples of the results of the numerical processing of the instrumental data, recorded during the first stage, are shown in Fig. 11 and Fig. 12, as follows:

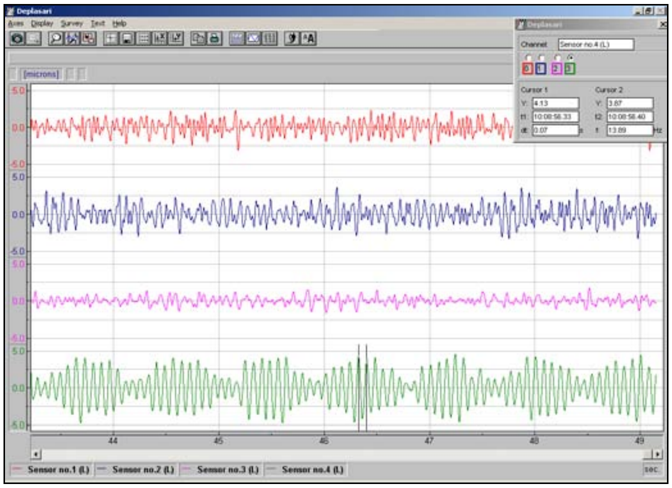


(a)

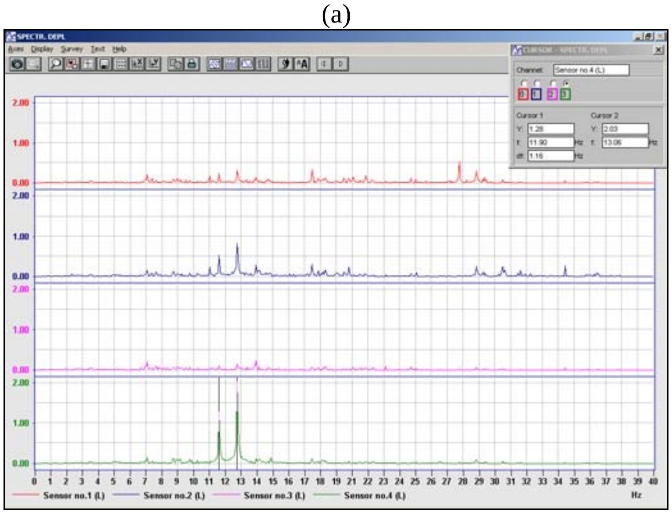


(b)

Fig. 11. Weaving shed – first configuration
Normal operation of all the weaving looms. Velocities [μm/s].
(a) - time domain; (b) - amplitude Fourier spectra.



(a)



(b)

Fig. 12. Flat roof of the weaving shed - third configuration. Normal operation of all the weaving looms). Velocities [$\mu m/s$]. (a) - time domain; (b) - amplitude Fourier spectra.

The *conclusions* of the first stage of the instrumental investigations that are of interest for the purpose of this paper are as follows:

- the two buildings were designed without having in mind dynamic loads of such intensity; that's why they were characterized by a high degree of sensitivity;
- despite the fact that the vibrations in the industrial building were very severe, they were not so dangerous for its structural system; due to the fact that the columns of the industrial building were fixed in the 38.5 cm reinforced concrete plate, the vertical vibrations generated by the weaving looms were transmitted directly to the prefabricated flat roof; their effects could be visible in time at the connections between the structural elements and the nonstructural ones, as a result of the different stiffnesses, as well as of the fatigue phenomenon;
- the strongly perceptible vertical vibrations were due to the rapier type weaving looms, working at a speed of about 420÷450 picks a minute (or frequencies of 7.06...7.50 Hz); for the industrial building the eigenfrequency of vibration on the vertical direction, instrumentally obtained, was 7.04 Hz; it is obvious that the driving frequency is close to the industrial building's natural frequency and the resulting motion is a harmonically frequency modulated vibration, illustrating the phenomenon of "*beats*"; practically, a "*beat*" means a pronounced increase of the dynamic system response;
- the same phenomenon was also present in the office building, whose eigenfrequency of vibration on the vertical direction was 7.3 Hz;
- *only the air-jet weaving looms make that the maxima of the transmitted forces coincide with the operating frequency; for the rapier type machines the maximum occurred at a frequency of higher harmonics.*

As remedial measures, adequate systems of isolation for all rapier type weaving looms were recommended, but it was also taken into consideration the possibility of intervention on the structural system of the office building.

The second stage

In order to establish the most suitable technical and financial measures, a second stage of instrumental investigations became necessary. This time the vibrations generated by the weaving looms were recorded only in the office building. Why was that? Because there were only two possibilities of intervention to be taken into consideration: to intervene on the "source" of the annoying vibrations, or to intervene on the structural system of the office building. But with what costs and who would support these costs? These questions bothered both the owner of the building and the Italian company. In this situation, R.N.C.E.E.V. decided to perform a technical assessment of the office building in order to establish the possibility of intervention, together with new instrumental investigations, knowing this time the source of the annoying vibrations.

The technical assessment of the office building revealed two surprises: one of them referred to the fact that during its construction the initial structure of foundation had been modified (see paragraph 3) and the other one was that the group of four interior columns with different cross sections at each floor responded with sonorous eigenvibrations. As the intervention on the office building could stop the activity, the owner didn't agree with this measure. That's why all the efforts have been directed on a new system of vibration isolators for the rapier type looms. The Italian manufacturer needed more data on the vibrations in the office building in order to create a new system of isolation.

In order to be able to give the necessary data and to eliminate any possible mistake, the following instrumental investigations were carried out in the second stage:

- the recording of vibrations on the vertical direction in order to identify the corresponding fundamental eigenfrequency;

- the recording of the vertical vibrations on three columns at the fifth floor, at the intersection of axes B – 3′, B – 2′ and A – 2′ (Fig. 13);
- the recording of the vertical vibrations on three panels of the slab at the fifth floor, in the area with the maximum perception of the noise (axes A – B and 1′ – 4′), in order to establish if the structural system induced waves are refracted by its slab surfaces (Fig. 13);

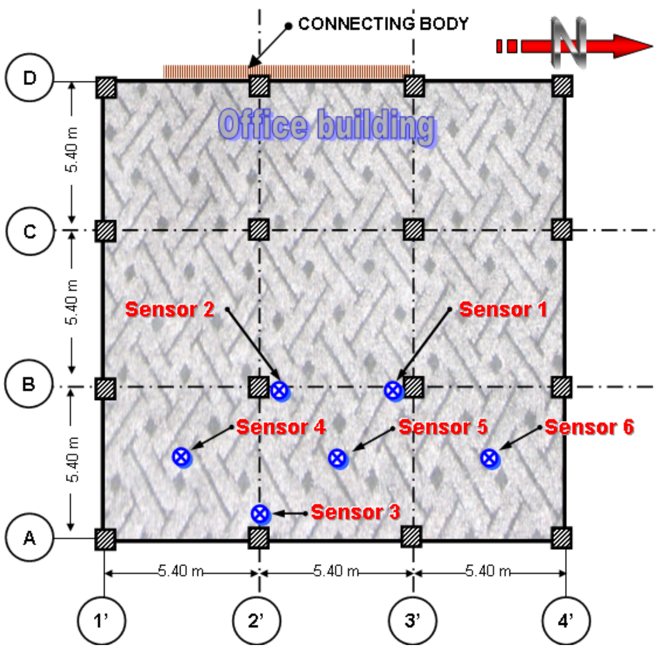


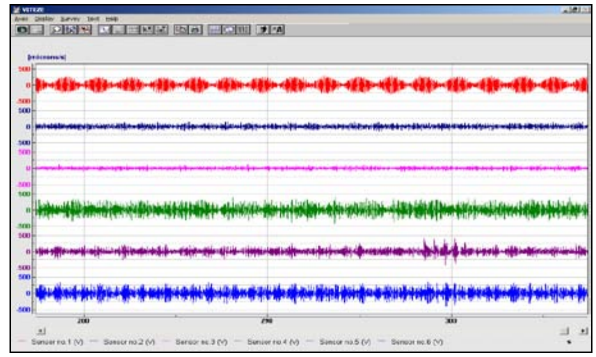
Fig. 13. Office building. Location of sensors at the fifth floor.

- the identification of the starting moment of the perception of the annoying noise, both by instrumental way and by the presence at the fifth floor of the building of four persons of different ages; firstly, the vibrations were recorded in the six locations already specified considering as source of vibrations the ambient vibrations on the site in order to establish the eigenfrequencies of the three columns and of the three panels of the slab; then, the 17 rapier type weaving looms were successively set in operation, one after another, the vibrations thus generated being recorded in order to observe the starting moment of the weaving looms running and their steady state operation.

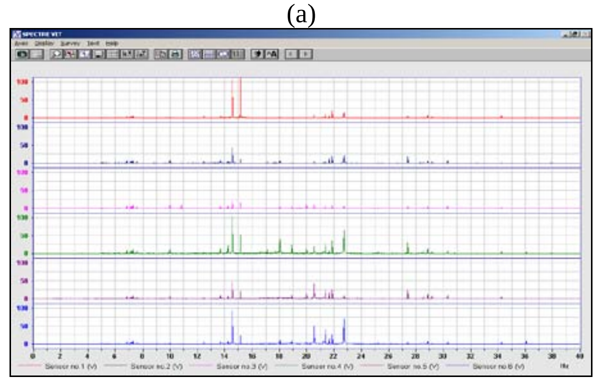
Typical time domain velocities and the corresponding amplitude Fourier spectra are shown in Fig. 14 and Fig. 15.

After performing the entire program of instrumental investigations a set of useful information was obtained.

In Table 1 are summarized samples of the obtained values in the case of the ambient vibration recordings and during the operation of the rapier type weaving looms, for all the directions considered.

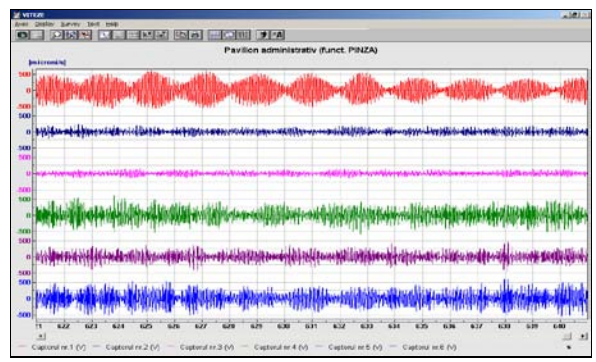


(a)



(b)

Fig. 14 . Office building. Normal operation of 4 rapier type weaving looms. Velocities [μm/s].
(a) - time domain; (b) - amplitude Fourier spectra.



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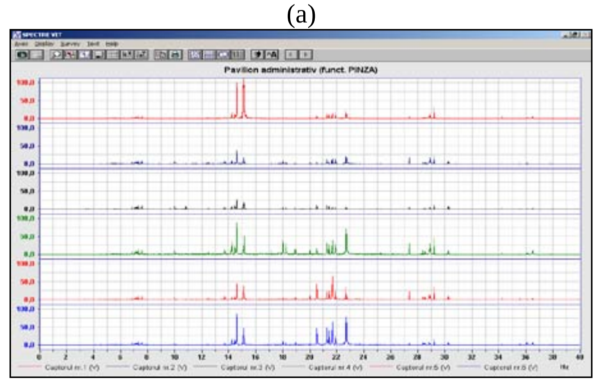


(b)

Fig. 15 . Office building. Normal operation of 11 rapier type weaving looms. Velocities [μm/s].
(a) - time domain; (b) - amplitude Fourier spectra.

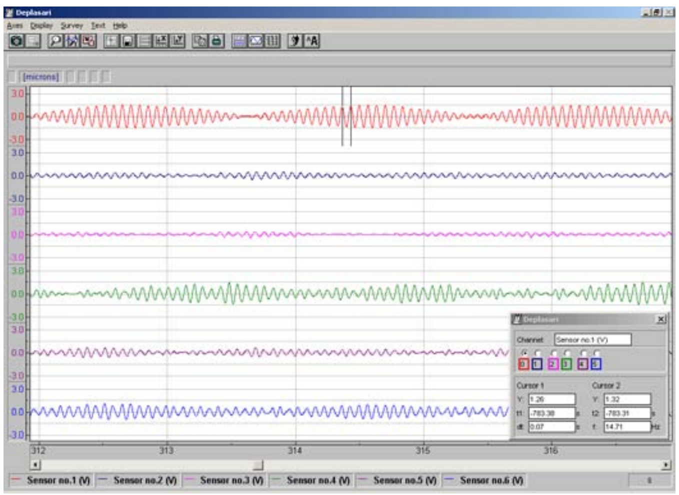
Table 1

Sensor no.	Source of vibrations	Identified frequencies [Hz]															
1	Ambient vibration	5.4	6.5	7.08	10	-	12.5	-	15.2	-	-	-	-	-	-	-	-
2		5.4	6.5	7.2	10	11.5	12.5	-	-	-	-	20	-	-	-	-	-
3		5.4	6.5	7.2	10	11.5	12.5	-	-	-	-	20	-	-	-	-	-
4		5.4	6.5	7.2	10	11.66	12.5	-	-	16.7	17.03	20	-	25.5	26.6	30	-
5		5.4	6.5	7.2	10	-	12.5	-	-	-	-	20	-	-	-	30	-
6		5.4	6.5	7.2	10	-	12.5	-	-	-	17.20	20	-	-	-	-	-
1	Operation of a single rapier type weaving loom	5.4	-	7.31	10.03	-	12.5	14.50	15.05	-	-	-	21.85	-	-	29	36
2		5.4	-	7.31	10.03	11.66	12.5	14.50	-	-	-	20	21.85	-	-	29	-
3		5.4	-	7.31	10.03	11.66	12.5	14.50	-	-	-	-	21.85	-	-	29	-
4		5.4	-	7.31	10	11.66	12.5	14.50	-	16.60	18	20	21.85	-	-	29	36
5		5.4	-	7.31	10	-	12.5	14.50	-	-	18	20	21.85	-	-	29	-
6		5.4	-	7.31	10	-	12.5	14.50	-	-	18	20	21.85	-	-	-	-
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
1	Simultaneous operation of 15 rapier type weaving looms	-	-	7.5	-	-	-	14.2...14.5	15.2	-	-	-	21.85	22.8	-	28.5...29.2	34...36.4
2		-	-	7.5	10	-	-	14.2...14.5	15.2	-	18	-	21.3...21.85	22.8	27.5	28.5...29.2	30
3		-	-	7.5	10	-	-	14.2...14.5	15.2	-	18	-	21.3...21.85	22.8	27.5	28.5...29.2	30
4		-	-	7.5	10	-	13.7	14.2...14.5	15.2	-	18...18.5	20.5	21.3...21.85	22.8	27.5	29.2	36.4
5		-	-	7.5	10	-	13.7	14.2...14.5	15.2	-	18...18.5	20.5	21.3...21.85	22.8	27.5	29.2	34...36.4
6		-	-	7.5	10	-	13.7	14.2...14.5	15.2	-	18...18.5	20.5	21.3...21.85	22.8	-	29.2	36.4
1	Simultaneous operation of 16 rapier type weaving looms	-	-	7.5	-	-	-	14.2...14.5	15.2	-	-	-	21.85	22.8	-	28.5...29.2	34...36.4
2		-	-	7.5	-	-	-	14.2...14.5	15.2	-	18	-	21.85	22.8	-	28.5...29.2	30
3		-	-	7.5	-	10.5	-	14.2...14.5	15.2	-	18	-	21.85	22.8	-	28.5...29.2	30
4		-	-	7.5	10	-	13.7	14.2...14.5	15.2	-	18...18.5	20.5	21.3...21.85	22.8	27.5	29.2	30...36.4
5		-	-	7.5	10	-	13.7	14.2...14.5	15.2	-	18...18.5	20.5	21.3...21.85	22.8	27.5	29.2	30...36.4
6		-	-	7.5	-	-	-	14.2...14.5	15.2	-	18...18.5	20.5	21.3...21.85	22.8	23.5	29.2	30...36.4
1	Simultaneous operation of 17 rapier type weaving looms	-	7.20	7.5	-	-	-	14.5	15.2	-	-	-	21.3...21.85	22.8	-	28.5...29.2	34
2		-	7.20	7.5	10	-	12.5	14.5	15.2	-	18	-	21.3...21.85	22.8	23.7...27	28.5...29.2	30
3		-	7.20	7.5	10	-	12.5	14.5	15.2	-	18	-	21.3...21.85	22.8	23.7...27	28.5...29.2	30
4		-	7.20	7.5	10	-	13.7	14.2...14.5	15.2	17.1	18...18.5	20.5	21.3...21.85	22.8	27.5	29.2	36.4
5		-	7.20	7.5	10	-	-	14.2...14.5	15.2	17.1	18...18.5	20.5	21.3...21.85	22.8	23.7...27.5	29.2	30...36.4
6		-	7.20	7.5	10	-	-	14.2...14.5	15.2	17.1	18...18.5	20.5	21.3...21.85	22.8	23.7	29.2	30...36.4

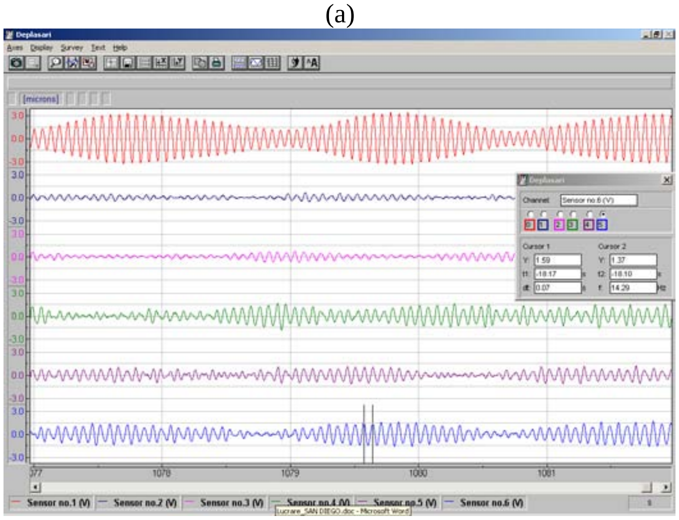
The *conclusions* of the second stage of the instrumental investigations were:

- the recorded data, both for “free” conditions (ambient vibrations) and for the “forced” ones (the running of the rapier type weaving looms), put into evidence a powerful tendency to a sinusoidal type configuration of the vibrations; this fact led to the conclusion that there existed a “powerful filtration” of these, due to eigenmodes of vibration of the structural system of the office building together with a reduced capacity of damping;
- the peak values of the recorded signals, practically for all time intervals, were reported on the column placed at the intersection of the axes B and 3′, and on the slab panels between the axes A – B and 1′–2′, respectively A–B and 3′– 4′;
- there is a sensitive tendency to non- synchronism of the recorded signals, both for the ambient vibrations as well as for the forced vibrations; this tendency is probably due to the powerful non-classical character of the eigenmodes (complex eigenvectors); it is difficult to consider a systematic character of non-synchronism, especially due to the complex dynamic system represented by this building;
- the study of the Fourier amplitude spectra put into evidence pairs of close marked spectral peaks around the values 7 Hz, 14 Hz, 22 Hz and 29 Hz; this result can be placed on the fact that there is a combination of two sources of vibration with close frequencies of operation (f=7.20 Hz, respectively f=7.50 Hz), which practically coincide with the fundamental eigenfrequency of the dynamic system represented by the office building (the measured frequency on the vertical direction is f_1=7.30 Hz, and the computed frequency on the same direction is f_1 = 7.14 Hz); *this was the case of dynamic system forced vibrations close to the resonance, followed by two levels of the phenomenon of beats*; the most pronounced spectral peaks are placed around the frequency of 14 Hz; thus, for the higher frequency (f = 7.50 Hz) the most pronounced spectral peak was identified for the interior column located at the intersection of the axes B and 3′; for the lower frequency (f = 7.20 Hz), the most pronounced spectral peaks were identified for the interior columns located at the intersection of the axes B and 2′ and for two slab panels (corresponding to sensors 4 and 6); there were also observed marked peaks for columns placed at the intersection of the axes A and 2′ and for the slab panel where Sensor 5 was placed (Fig. 13);

- as one can notice, the most pronounced spectral peaks were placed around the frequency of 14 Hz, in close vicinity of the lower limit of frequencies perceived by the human ear;
- marked spectral peaks were also identified for frequencies of superior order III and IV, at values equal to 22 Hz and 29 Hz;
- the phenomenon of acoustically perceived beats was well correlated with the obvious “beat” character of the records in time domain (filtered or non-filtered);
- the examination of strongly filtered records in the frequency intervals 14 Hz÷14.9 Hz and 15 Hz÷15.5 Hz pointed out some supplementary aspects (Fig.16 and Fig.17):
  a) for the lower amplitude of the disturbance, strong “beats” were signaled especially for the column placed at the intersection of axes B and 3′ and for the slab panel placed between axes A B and 1′ – 2′; practically no beats were observed in the slab panel placed between A – B and 2′ – 3′;

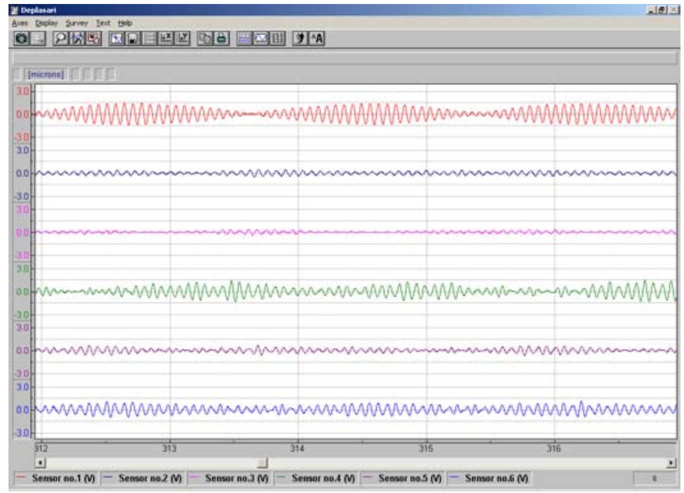


(a)

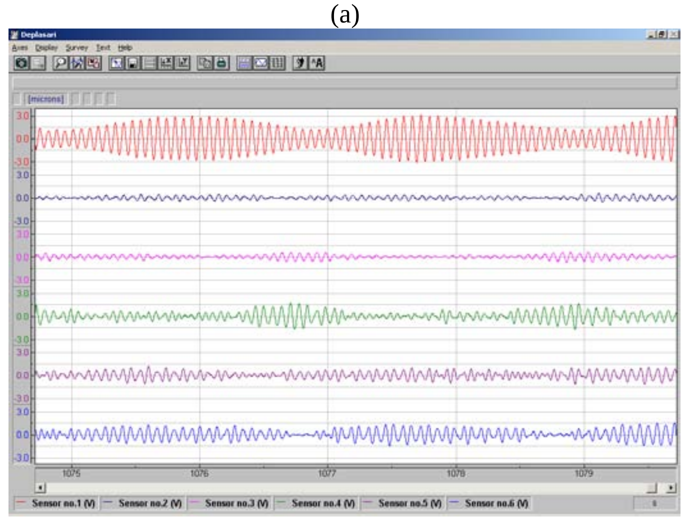


(b)

Fig. 16 . Office building. Normal operation of 5 (a) and 17 (b) rapier type weaving looms. Signal filtered in the interval 14...14.9 Hz. Displacements [μm].



(a)



(b)

Fig. 17. Office building. Normal operation of 5 (a) and 17 (b) rapier type weaving looms. Signal filtered in the interval 15...15.5 Hz. Displacements [μm].

  b) for the maximum amplitude of the disturbance an attenuation of the “beats” phenomenon was signaled, for the column placed at the intersection of axes B and 3′, but marked “beats” in the slab panel between axes A – B and 3′ – 4′;
  c) minor changes of the general character of vibrations were observed when passing from a filtering band to the other (fact that was somewhat surprising), but more important changes of their aspect when passing from an amplitude of disturbance to the other.

THE CHECKING OF THE INSTRUMENTAL FINDINGS

From theoretical point of view, the fundamental period of vibration for the vertical direction of the building can be estimated by using the relation:

$$T_{1,VERTICAL} = 0.2\sqrt{x_{ST}} \quad (x_{ST} \text{ is expressed in “cm”}) \qquad (1)$$

where "x_{ST}" in the above formula is "*the total settlement*" corresponding to the whole mass of the building. Taking into account that the supporting ground at the location of this building is of macroporous type, a total settlement equal to 5 cm was considered. Thus, the value of the eigenperiod of the building for the vertical direction, after "*the settlement reached its final value*", has resulted:

$$T_{1,VERTICAL} = 0.2\sqrt{5} = 0.45 \text{ s } (f_{1,VERTICAL} = 2.22 \text{ Hz}) \quad (2)$$

At the time when the instrumental investigations were carried out, the supporting ground beneath the isolated foundations of the building was consolidated and the mechanical characteristics related to its deformation were definite, as a result of the ending of the settlement process. The eigenperiod $T_{1,VERTICAL} = 0.45\ s$ corresponds to the situation when the settlement on the vertical direction is ended and the supporting ground beneath the isolated foundations of the columns can be considered compact.

As we already know, the vertical vibrations generated by the operation of the 17 rapier type weaving looms in the industrial shed were transmitted by the macroporous medium to the isolated foundations of the office building. The building is set in a vertical vibrations process, which is due to the *deformation* of the supporting ground already compacted, at the existing interface between the bottom of the isolated foundations of the columns and the supporting ground.

In the following, the new vertical fundamental period of vibration corresponding to this situation will be assessed, due to the changes in the deformability characteristics of the supporting ground for vertical vibrations.

As the technical literature does not provide real values for the deformation modulus for macroporous soils and there was no recent information on the actual supporting ground, as well as on the building foundations, based on own experience it was considered a deformation modulus of the supporting soil on the vertical direction (to dynamic actions) ten times greater. In other words, if initially it was considered a total settlement equal to 5 cm, as a result of the present dynamic regime of solicitation, the supporting ground will suffer settlements ten times smaller, approximately equal to 0.5 cm.

In this situation, the fundamental period of vibration corresponding to the vertical direction will have the value:

$$T_{1,VERTICAL} = 0.2\sqrt{0.5} = 0.14 \text{ s } (f_{1,VERTICAL} = 7.14 \text{ Hz}) \quad (3)$$

As a result of this simple reasoning, one can notice that the value of the fundamental eigenfrequency for the vertical direction, established above ($f_{1,VERTICAL}$ = 7.14 Hz), is confirmed by the instrumental investigations, within which was obtained a value $f_{1,VERTICAL}$ = 7.30 Hz.

HOW TO EXPLAIN THE ANNOYING VIBRATIONS

During the operation of the 17 rapier type weaving looms in the weaving shed, a general reinforced concrete plate of about 6000 square meters and 38.5 cm in thickness is set into a vertical vibratory motion. These vertical vibrations were transmitted to the underneath supporting ground which was also involved into a vertical process of vibration. Taking into account the existing soil conditions and the reduced distance between the weaving shed and the office building, the vertical motion was transferred in the vicinity where it encountered the supporting ground of the office building and its structural system. The excitation of the office building in the close vicinity of the weaving shed through the soil was influenced primarily by the transmission properties of the soil. Because of the inhomogeneity of the ground, the transmission mechanism was very complicated.

Unfortunately the vertical pulses of motion didn't encounter an actual structure of foundation. The configuration of the office building's structure of foundation consisted only in isolated columns foundations, without interconnecting foundation beams. This fact favored their independent vertical vibration and, more than that, the whole structural system's vibrations as well. In other words these isolated foundations were set into vertical vibrations and due to the lack of foundations beams, favored the transfer of the vertical waves to the superstructure of the office building. The intensity and frequency content of the office building's vibrations induced by ground transmitted waves were governed by the excitation source, the directly transmission path, and the properties of its structural system as a *receiver*. The multitude of parameters involved precludes an exact solution of the vibration problem. Therefore the effects of pertinent parameters need, in general, to be determined by experience and measurements. The transmission medium plays an important part in this process.

The instrumental investigations and *in situ* observations revealed that the mechanical vertical vibrations of the columns isolated foundations are induced through the columns in the whole building (to its floors, partitions and exterior walls). These vibrations are perceived in the building as "*acoustic waves*", especially at its fifth floor. It is an extremely rare case, when mechanical vibrations transmitted at distance are accompanied by a permanent noise with exceedance of thresholds of high intensity at very short intervals of time.

It must be remembered that the cross section of all the interior columns differs from floor to floor, at the last two floors being 0.35 m x 0.35 m. The instrumental investigations of the vertical vibrations performed on the last floor of the office building, with sensors placed directly on the columns, revealed important differences in their response and an independent behavior. At the interior columns, the presence of vibrations near resonance was certified; thus the phenomenon of "*beats*" was present and perceived as an acoustic annoying noise. The waves induced to the structural system were refracted by the reinforced concrete floor and wall surfaces as an "*indirect sound*", unpleasantly perceived, as the people working inside could not localize its source.

As a conclusion, the vertical vibrations generated by the 17 rapier type weaving looms were perceived in the office building, especially at its fifth floor as "*sounds*" that were intercepted as "*dull sound*" (thud), due to the perception characteristics of the ear. At some time intervals the noise was amplified to "*thresholds of feeling*" (of high intensity), which created an extremely annoying sensation.

CONCLUSIONS

a) A study of the dynamic response of two different types of buildings due to vertical vibrations generated by the operation of weaving looms in a weaving shed has been performed.

b) In an office building placed in the very close vicinity of the weaving shed annoying acoustical vibrations were signaled, especially in the rooms of the top floor; these vibrations generated even undesirable actions on human comfort in the whole building, and repeated disturbances to sensitive electronic equipment. The phenomenon of "beats" acoustically perceived was present in the response of the dynamic system represented by the office building, as a result of the fact that the disturbing source (rapier type weaving looms) had a "*permanent*" character (operating more than 8 hours a day) and the transmitted vertical vibration presented a strong tendency to harmonic type of waves. As a result that this tendency is also present in the "free" vibration conditions (ambient vibrations on the site, road traffic and technological processes in the near vicinity), one can state that this fact is favored by the structural system configuration of the office building and its reduced capacity of damping. The second condition of the presence in the dynamic response of the phenomenon of "beats" is also accomplished, as the frequencies of the sources (f = 7.20 Hz and f = 7.50 Hz for the two rapier type weaving looms) are very close to the fundamental eigenfrequency of the dynamic system on the vertical direction, instrumentally obtained (f_1 = 7.30 Hz), but *not* equal (response in the resonance vicinity).

c) First of all it was necessary to identify which type of weaving looms was responsible for generating the annoying acoustical vibrations. After performing a complex program of instrumental investigations in two stages, the rapier type weaving looms was found responsible for these. It must be mentioned the fact that these weaving looms were installed in an old industrial building, not designed for such equipment, together with the fact that the supporting soil is of macroporous type, which favored the propagation of the vertical mechanical vibrations.

d) Due to the local conditions, any other solution to stop the transfer of the vibration energy induced by dynamic sources (as an example the use of artificial barriers) was considered difficult, expensive and possibly ineffective; that's why the attention was focused on the "*source*" and on the "*system*".

e) The technical assessment of the two buildings was also performed in order to establish a solution for avoiding the vibration problems. During this process, faults in the design project and in the construction of the office building were identified. Among them, two structural deficiencies (the structure of foundation and the reduced cross sections of the columns at each floor) were the ones that favored the annoying acoustical vibrations. As the costs for the remedial measures for the five levels office building were high and they were not approved by the owner, an intervention on the vibration source remained as the unique solution. In general, the most effective method is the *reduction* of the energy of the vibrations at the *excitation source*. In this case, the excitation source was treated as an entity, by considering the process of isolation, damping and attenuation with the objective of reducing the propagated vibrations. Thus an agreement was reached by taking the decision to replace the system of isolation of the rapier type weaving looms.

f) The associated phenomena to this intervention being extremely complex imposed the initiation of a costly research program, entirely sustained by the owner of the weaving looms, both in Romania and in Italy. Based on the first stage instrumental investigation results, the Italian manufacturer asked a specialized company from Italy to carry out a "*system of isolation*", capable to avoid the excessive vertical vibrations perceived both in the weaving shed and in the office building. Two systems of isolations were tested. The first type was set at two weaving looms and the second one was set at two other weaving machines. The results obtained by instrumental investigations were that the level of vibrations in the weaving shed was reduced, but the annoying effects at the fifth floor in the office building still persisted. In this situation, the two systems of isolation were tested in the laboratory of R.N.C.E.E.V. The obtained results led to the necessity of performing new instrumental investigations in the office building. This was the story of the second stage of instrumental investigations when three sensors were mounted directly on three columns and other three on three panels of the general slab of the fifth floor of the office building. The conclusions that have resulted were presented in paragraph 4.2. As it was established that the two systems of isolation could offer neither the warranty of reducing the level of vibrations and, more than that, nor the annoying permanent noise at the last floor of the office building, the decision to design a new system of isolation was taken. An engineer of a specialized company in weaving looms vibrations isolation, together with the owner of the equipment arrived in Romania to evaluate *in situ* the actual situation. Based on the second stage results of the instrumental investigations, a new type of "isolators" was created by the Italian company "ST – Soluzioni Techniche" (Fig. 18). The system of isolation reduced the vibrations on both horizontal and especially in the vertical direction. After setting up these isolators the level of vibrations in the two buildings was substantially reduced. The permanent noise, but in principal the exceedance of "*thresholds of high intensity*", extremely annoying, which have produced the phenomenon of "acoustical fatigue" have also disappeared.

Fig. 18. The new system of isolation for the rapier type weaving looms.

Thus the problem was solved and the author considers that this experience of nearly two years of hard work, research and money spent is worth to be known.

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