Structural Assessment by Modal Analysis, case study of the new Algiers Airport

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Abstract

The assessment of the structural resistance of existing constructions such as buildings, bridges, dams etc. uses often mathematical models whose parameters can hardly be precisely estimated by analytical procedure only. Therefore, the elastic, mass and damping characteristics of the structure to be assessed must be known to a sufficient degree of accuracy in order to evaluate the actual structural capacity of the construction. The elastic dynamic properties, particularly the natural frequencies and the corresponding mode shapes are a combined measure of the structural characteristics of the construction. These model characteristics can be successfully estimated, especially in elastic range, using the well known ambient vibration testing. In this paper, the assessment procedure of the new Algiers airport building is described. The results of an extensive program of non-destructive and destructive tests on the concrete were put into the equations, and series of ambient vibration tests were conducted and modal analysis were performed to validate the mathematical models. The paper concludes that a complete program including both non-destructive and ambient vibration testing is essential to accurately validate the hypotheses of the numerical modelling and eventually evaluate the resistance capacity of the structure.

Keywords: Structural Analysis and Design - Dynamic Analysis - Finite Element Analysis - Structural Modelling - FEM in Design - Damage Identification.

1 Introduction

The ability to assess structural damage of existing constructions has been interest to engineers for a long time ago. The most common forms of deterioration are concrete degradation, corrosion and fatigue related damage. Over the years, a range of techniques has been developed for the inspection of structures. Among others, conventional, though efficient, methods such as visual inspection and non-destructive testing are widely used to diagnostic and to evaluate damaged constructions. The information obtained can be very valuable for both damage identification and material properties updating in finite element modelling. In many cases, however, the overall performance may not be adequately estimated solely by these methods.

The vibration data is an attractive way to extract some global characteristics such as the natural frequencies, damping ratios and mode shapes. Particularly, the ambient vibration testing which is appropriate for experimental modal analysis has been used for a long time in investigating the dynamic behaviour of structures at low vibration amplitudes [1,2]. Recently, many techniques have been developed for detection, location and characterisation of structural damage by dynamic testing taking into account some environmental effects such as the temperature and the excitation sources [3]. Some of these methods were successfully applied in simulation examples and very controlled experiments [4,5,6]. Powerful identification techniques that are able to locate damage based on realistic measured data sets still seem a long way from being achieved [7]. This paper propose a generalised procedure for practical use of ambient vibration testing in conjunction with analytical modelling for assessment of the global structural condition of large civil engineering constructions.

2 Technical description of the construction

The new Algiers airport is designed to operate at first stage for a capacity of five million passengers/year with two distinct modules C and D structurally and functionally autonomous. Each unit is composed of five (05) zones which are themselves subdivided into several blocks (Figure 1).

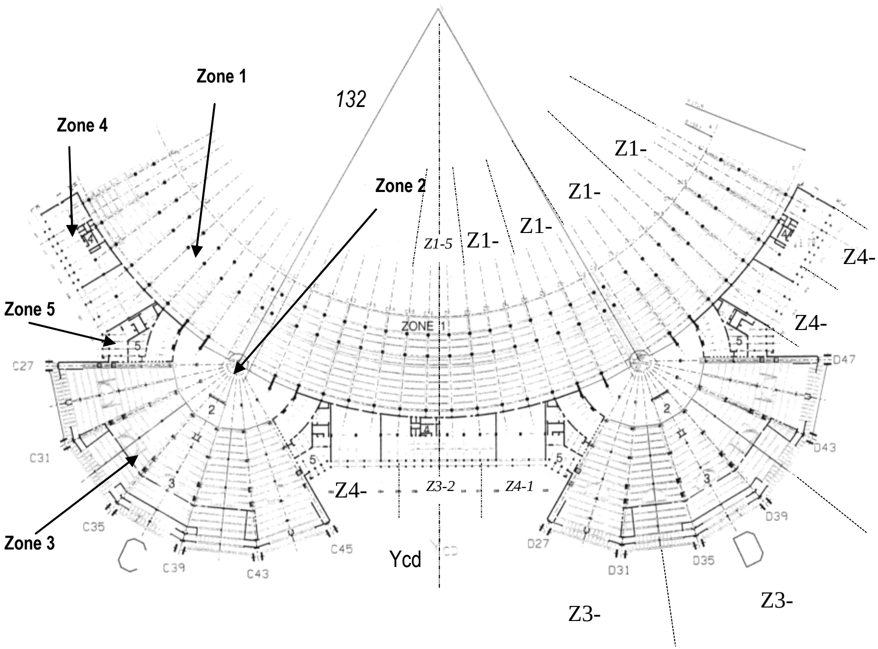


Figure1: Plan view of the New Algiers airport.

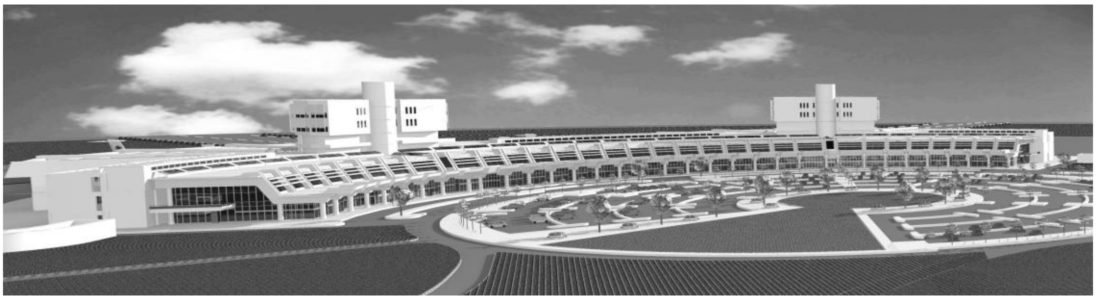


Figure 2: General view of the new Algiers airport.

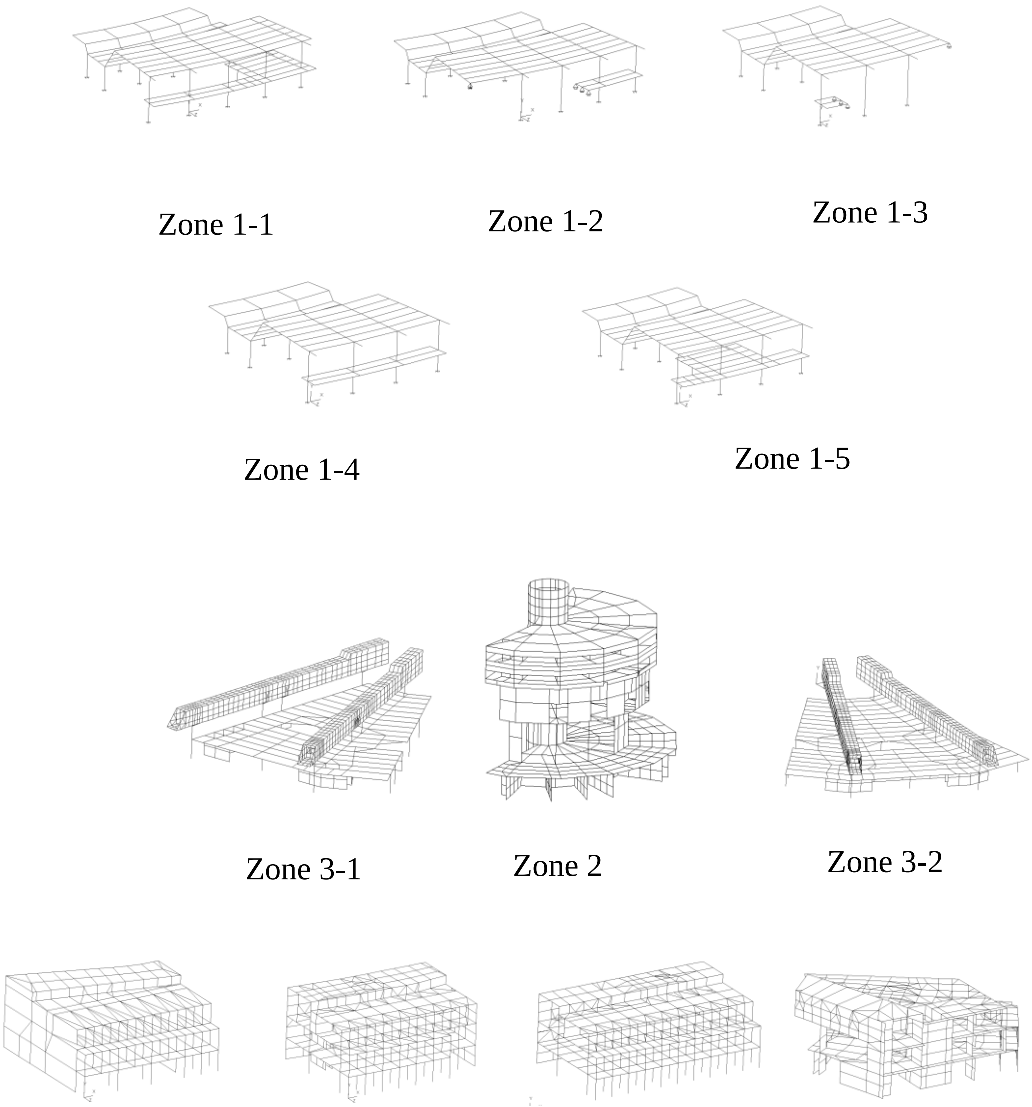
The structural system is strongly affected by a potent architecture resulting in massive reinforced concrete frames strengthened by walls. Because of the weak nature of the soil the whole structure is founded on deep piles.
The construction of the building started in 1986 and stopped two years after completing 90% of the concrete superstructure. Following a long status quo of the exposed concrete structure, the latter suffered several deteriorations besides the poor material properties (Figure 3). This work is part of a large structural survey lunched to give a new lease of life to this project.

Figure 3: General view of the actual construction.

3 Technical description of the construction

With regard to the geometric complexity of the different block construction, only 3D models can predict the elastic dynamic behaviour of the structures with sufficient precision. These would results in large and complex Finite Element (FE) models with several ten thousands degrees of freedom. However, for practical reason, the modelling is kept simple within the limits of the civil engineering profession where for this particular case the mathematical models are intended to simulate the overall structure performance which will be ultimately used for resistance and stability assessment and eventually for structural strengthening. In the first instance, use was made of the numerical models for optimisation of the measurement point plan as described subsequently.

The structural analysis and design software STAAD III was used to perform all the numerical modelling and analyses. All structural members having one preponderant dimension such as columns and girders were modelled as beam elements, reinforced concrete walls and floors are modelled by plate elements with coarse mesh except for specific regions identified as either weak or potentially with high stress concentration which have been their mesh refined. The structure was assumed to be fixed at ground level. The material characteristics of the reinforced concrete are very irregular. The mean value suggested by a mission on the material quality assessment was used throughout the analyses and found to be adequate. Thus we obtained 20 different models. The most representative are shown below (Figure 4).



Zone 1-1 Zone 1-2 Zone 1-3

Zone 1-4 Zone 1-5

Zone 3-1 Zone 2 Zone 3-2

Zone 4-1 Zone 4-2 Zone 4-3 Zone 5

Figure 4: Finite element models.

4 Preliminary modal analysis (sensors locations)

As mentioned before, the structure is very large and complex and no trivial mode shapes are apparent. This would require a large number of sensors and testing measurements to identify the dynamic characteristics of the different bloc structures. Therefore, the definition of a measurement point plan prior to testing is essential [8]. This is usually based on the results of mathematical predictions and on engineering judgement, which can contribute to find a maximum of structural information with a minimum number of measurement points.

The test data are used for updating the FE models, therefore priority is given to fundamental modes to be accurately measured. By means of a sensitivity analysis, the influence of the modes with respect to uncertain structural parameters was calculated. This allowed separating the modes into those with higher and lower importance with respect to the updating process.

For this particular case preliminary modal analyses were carried out and the fundamental modes were predetermined. On the base of these results optimum sensor locations were chosen nevertheless additional measurement points were also included to take account of any other modes that were not predicted by the analytical model. Measurement near the nodal point of any of the modes will omit that particular mode and aliasing effect is to be prevented by avoiding intersection regions of the fundamental modes to be identified.

5 Ambient vibration testing

Today, ambient vibration testing has become widespread as a fast and economical means of finding the modes of vibration of structures. It has reached the stage of being fully computer-based, which has made its application very efficient. In this paper we present briefly the main issues pertaining to this particular modal testing; FRF measurement techniques, testing procedure, and modal parameter estimation method.

On the basis of the preliminary modal analyses, an appropriate test programme was tailored to allow an optimum use of a limited test time.
The tests were performed by the National Earthquake Engineering Research Centre (C.G.S) using a KINEMETRICS ambient vibration set composed of seismometers type and a data acquisition station type SSR-1. The measured signals were processed using the MAC/RAN program specifically developed for the analysis of ambient vibration data.

The sensors were located and oriented according to the previously defined test programme. To reach all measurement points with 100m long cables, two or more centre locations had been used for large structures and the work was broken down into phases. The recording time for each sequence was set to 10 mn and found to be largely sufficient to obtain smooth transfer function curves. In total 12 blocs were instrumented and tested (Figure 5).

Figure 5: Ambient vibrations testing on the cell-box girder.

5.1 Determination of natural frequencies

The natural frequencies of the different structures were simply identified using a "peak cursor" on each set of the transfer function curves. Due to the complex shape of most of the tested structures, the individual vibration modes do not exhibit purely translational motions, but generally a coupled transversal, longitudinal and rotational motion. Thus individual Frequency Response Functions (FRF) have peaks corresponding to several modes. In one hand this enables to cross-check the measured frequencies but in the other hand closely spaced frequencies are difficult to identify.

In total, more than 36 frequencies were identified (Table 1). Due to space limitation only few FRF curves are presented here. Figure 6 shows the FRF of the transverse accelerations measured on the centre of the top floor of the tower (zone 2). The clearly defined peak at 2.60 Hz corresponds to predominantly first mode (translational). The FRF for the longitudinal acceleration records obtained on the centre of the semi-circle floor zone 2 is shown on Figure 7. In this figure a small peak can be observed at the frequency of 3.95 Hz indicating a smaller longitudinal component of the third mode (coupled longitudinal-torsional). The second mode (torsional) does not appear on this curve, but it can be clearly seen on the FRF of the acceleration recorded on the edge of the semi-circle floor, which reveals the torsional component of the second mode at a frequency of 3.10 Hz.

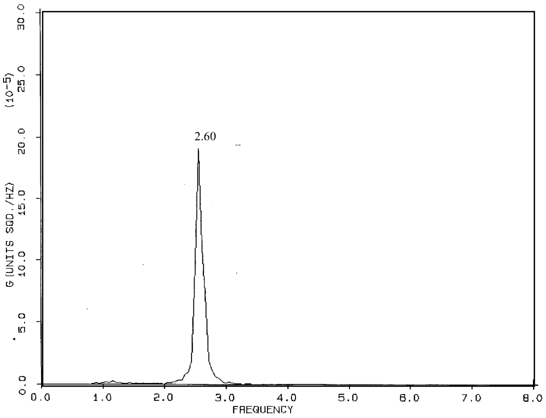


Figure 6: Frequency Response curve Zone 2.

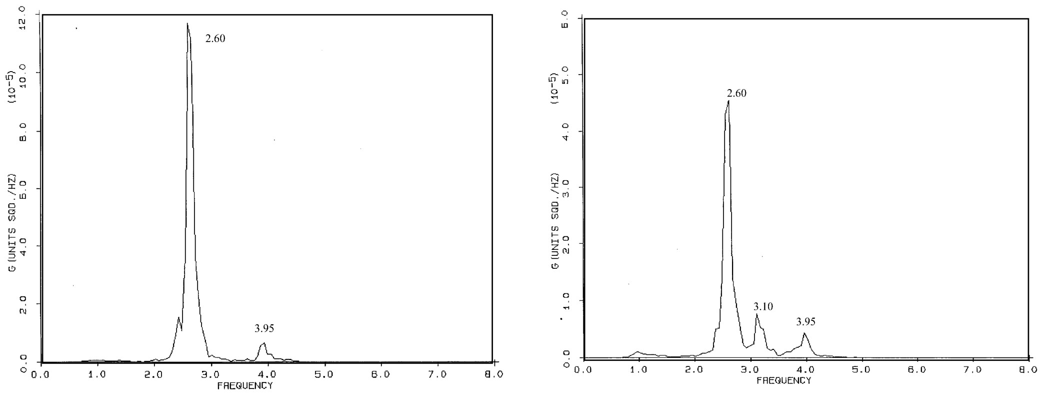


Figure 7: Frequency Response curves Zone 3.

5.2 Determination of modes shapes

Because of time and cost constrained by the objectives of this work, a small subset of the FRFs has been measured on the cell-box girder structure (zone 3) as depicted in Figure 8. Yet, from this small subset of FRFs, we can accurately define the modes that exhibit the behaviour of the neoprene supports of these girders. Of course, the more we partially sample the surface of the structure by taking more measurements, the more definition we will give to its mode shapes.

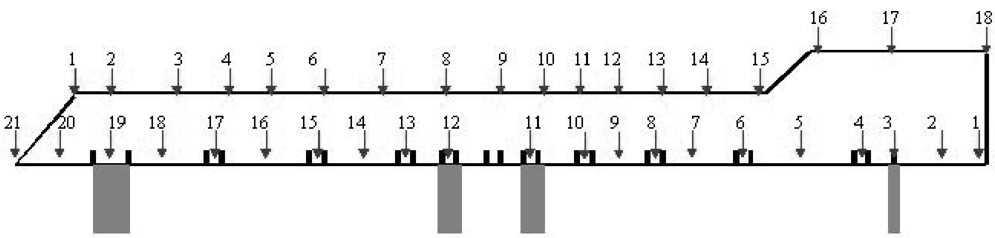


Figure 8 Sensors locations on the cell-box girder

6 Experimental modal analyses interpretation

Using the actual material properties obtained by Non-Destructive and Destructive Testing, excellent correlation between experimental and analytical natural frequencies is achieved in most cases as can be seen from Table 1.

Table 1: Calculated and measured natural frequencies

Bloc	Mode	Experimental (Hz)	Analytical (Hz)	Error (%)
Z11C	1	3.90	3.11	20.25%
	2	4.50	4.57	01.55%
	3	6.50	5.38	17.23%
Z12C	1	2.65	2.64	00.38%
	2	3.20	3.34	04.37%
	3	4.15	4.69	13.01%
Z2C	1	2.60	2.50	03.84%
	2	3.10	3.04	01.93%
	3	3.85	3.90	01.30%
	2	3.50	3.35	04.28%
	3	4.40	4.60	04.54%
Z3C	1	3.05	3.05	0.00%
	2	3.40	3.37	0.88%
	3	3.95	4.04	2.27%
	4	4.45	4.60	3.37%
	5	5.85	5.91	1.02%
	6	6.50	6.13	6.03%
Z3D	1	2.90	3.00	3.44%
	2	5.70	5.71	0.17%
	3	6.50	6.47	0.46%
Z41C	1	3.90	4.12	7.01%
	2	8.60	7.75	9.88%
	3	-	10.90	-
Z51C	1	7.00	6.99	0.14%
	2	-	8.55	-
	3	-	11.17	-

The correlation between experimental and analytical modal data is used as mean of detecting eventual anomalous structural behaviour exploiting the sensitivity of modal parameters to physical alterations.

In first instance, an evident discrepancy between the first and third natural frequencies of the bloc Z11 is attributed to the malfunctioning seismic joints between two adjacent blocs where the lateral translation component is partially prevented. The measured frequencies of Zone 2, however, were in good agreement with analytical predictions. This is mainly due to the fact that the bloc is fully detached which reduced considerable the interference with adjacent blocs. Other important observations are the successful identification of local flexibilities of the incomplete cell-box girder of the bloc Z3C as can be seen in figure 9, the frequencies 3.40 Hz, 3.95 Hz and 4.45 correspond to the local vibration modes of the vertical walls of the cell-box girder.

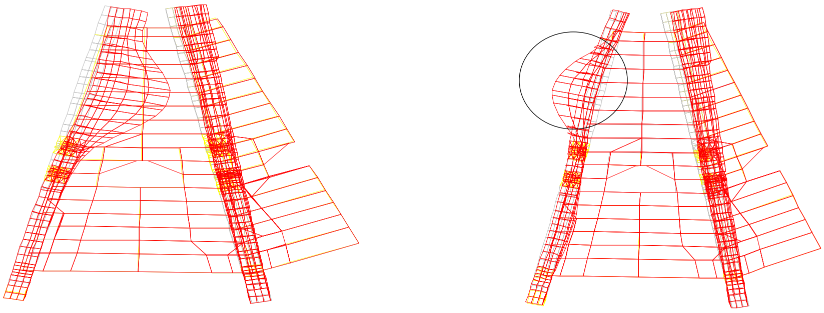


Figure 9: Local flexibilities of bloc Z3C.

The fundamental mode shape of the cell-box girder represented by the measured points along the longitudinal centre line of the upper side as plotted in figure 10 is identical to the corresponding analytical mode shape. It can be noted also that the shape of the first mode shows a continuous deformation along the girder which confirms the relative flexibility of the neoprene supports.

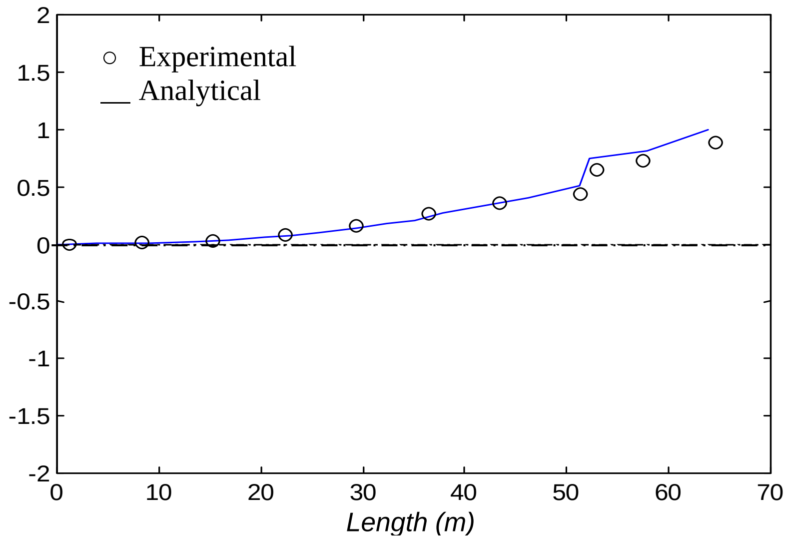


Figure10: Measured and calculated second mode shape of bloc Z3-1C.

The Destructive and Non-destructive Testing which showed better material characteristics of module C have been confirmed by the ambient vibration testing where the blocs of module C tend to have higher frequencies than those of similar blocs of the module D. Furthermore most of the measured frequencies matched the corresponding calculated frequencies in excess which corroborate the analytical hypothesis and exclude major structural damages in the construction.

7 Conclusion

This work is a contribution to generalise the use of ambient vibration method combined with simple FE modeling in ordinary diagnostic mission of civil engineering structures.

In the light of the results obtained for this particular case, the following observations are noteworthy:

- For practical reasons a preliminary modal analysis is essential to optimize the sensor locations.
- The ambient vibration testing sensitivity to material characteristics is acceptable for ordinary diagnostic purposes of such civil engineering constructions.
- Local flexibilities and imperfect seismic joints can be detected using the ambient vibration tests together with simple FE models.
- The analytical and experimental correlation gives an indication of the overall integrity of the structure in accordance with the hypotheses of the FE models.

Acknowledgement

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